Nuclear Astrophysics
Prof. Anil Kumar Gourishetty
Department of Physics
Indian Institute of Technology, Roorkee
Module - 01
Lecture - 05
Evidence of Nucleosynthesis - II

Welcome students. I hope you are able to get some idea about the evidence of nucleosynthesis which has been happening in the universe from the time of big bang. Let me quickly summarize the previous lecture where I have addressed a query that for how long the solar abundance distribution got operated. It was about 10 billion years considering the phenomenon of cycling processes between a star and the interstellar medium.

Then I have provided some information about the categorization of nucleosynthesis which is basically the process of formation of new nuclides due to nuclear reactions. What are those three categories? Number one; primordial nucleosynthesis which is essentially the reason for the formation of H and He and cosmic ray interactions which leads to the formation of Li, Be and B.

Then beyond B starting from C and beyond C it is called stellar nucleosynthesis. Then we have seen how the discovery of ^{99}Tc by Paul Merrill in 1952 using the observatory has changed the way researchers used to see the world. So, the view with which people are looking at the world has dramatically changed because of this discovery. See not frequently discoveries will change the world view.

But this was the one which changed the view of the world regarding the synthesis of elements in the universe. How elements got synthesized in the universe? So, in a nutshell I wanted to convey in the previous lecture that because no isotope of the Tc is stable and with the telescope the emission and absorption spectrum has given a clear indication of the presence of Tc. You have to understand because it is not an astronomy course I am not going into the details of those measurements.

How that line in the spectrum was recognized or identified as technetium? Those details I am not going. So, this is the limitation of my course and as I said in the very first class it is basically the role of nuclear physics in the stars. But it was very well established that the Tc was very much present in the spectrum recorded by the telescope which was handled by Paul Merrill. The half-life of the most long-lived isotope of Tc is about 4 million years ago.

At first instance you may think that 4 million years ago, four million is a very big number but at a cosmological scale when you talk about billion years, it is very less. So, at cosmological scale it is the same 1959 to 2021. So, now if we are able to detect the Tc it means the synthesis is happening even now. So, it is a recently produced Tc and later people could reproduce it with different facilities.

After that I have given some information about one of the important applications of the isotope of Tc that is ^{99m}Tc which is widely used in medical field as a radio tracer. A radio tracer is something which is used for the diagnostic purpose. It is inserted within the body and when it emits the radiation through some tumour or some kind of disorder in the body, the counts or the number of gamma rays will be different when compared to the normal parts of the body. That change in the number of gamma rays through the disordered section and normal section of the body will tell the presence of the disease in the body. So, what is metastable state? Nucleus when it has different levels, the transition from higher to lower level happens within femto or picoseconds sometimes you know microseconds.

But there are a few excited states in a few nuclei whose half-life is like milli seconds, minutes and hours. These are called as isomers. So, some of you who have already been taught basic physics in you BSc level you might be aware of it. But if after plus two you are taking this course, I think this terminology will be useful to you. So, isomer is something which is having relatively longer half-life regarding the transition from higher state to lower state.

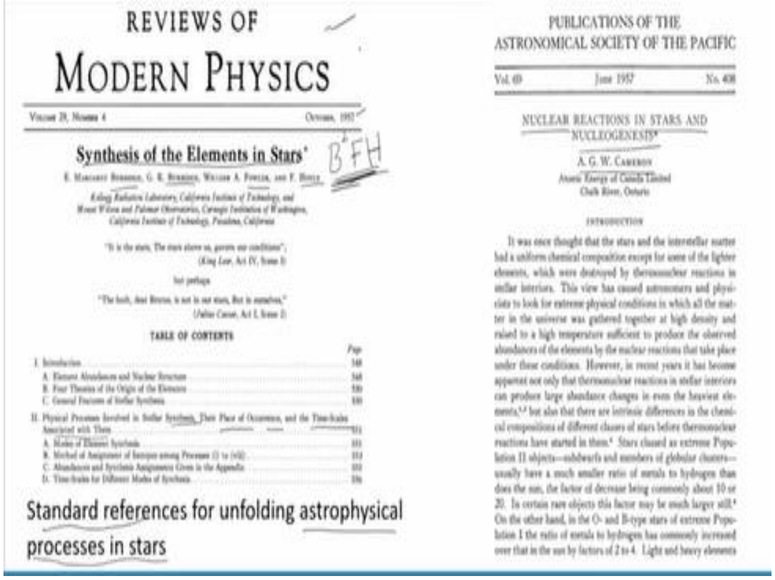
If you are aware of the concept of lasers where metastable states are mandatory to have then only population inversion is possible. Without metastable states the population inversion is not possible and one cannot get the laser. That is the reason nowadays researchers are exploring to make gamma-based lasers which are termed as gazers. Because now isomers you know are in plenty and people have gained enough knowledge about the isomers.

Using these isomers which are having metastable states nature one can produce gazer. It can be extended to some kind of gazer concept that is one of the emerging areas in the nuclear field. Anyway, coming back to our course, so this ^{99m}Tc state is produced from the Mo which can be produced as part of the fission of uranium. And because molybdenum has about 2.75 days half-life within that time it is easy to ship the molybdenum to medical facilities.

This ^{99}Mo is radioactive it is decaying to ^{99m}Tc state and that is having 6 hours of life and emitting about 140 keV gamma line. You measure the intensity of this gamma line and know the disorders within the body. So, do you remember what exactly we are trying to understand at this stage, we are looking for evidences for nucleosynthesis.

One of the important evidence I have discussed, the discovery of technetium which has changed the way researchers looked at the world. Like technetium, the discoveries of many other phenomena and many elements when people came to know then some beautiful work has been compiled by few astronomers. I am going to show you the standard paper, the standard references in nuclear astrophysics. So, I strongly suggest you to go through these papers.

(Refer Slide Time: 08:37)



REVIEWS OF

MODERN PHYSICS

Synthesis of the Elements in Stars

B²FH

PUBLICATIONS OF THE
ASTRONOMICAL SOCIETY OF THE PACIFIC

NUCLEAR REACTIONS IN STARS AND NUCLEOGENESIS

A. G. W. CAMERON

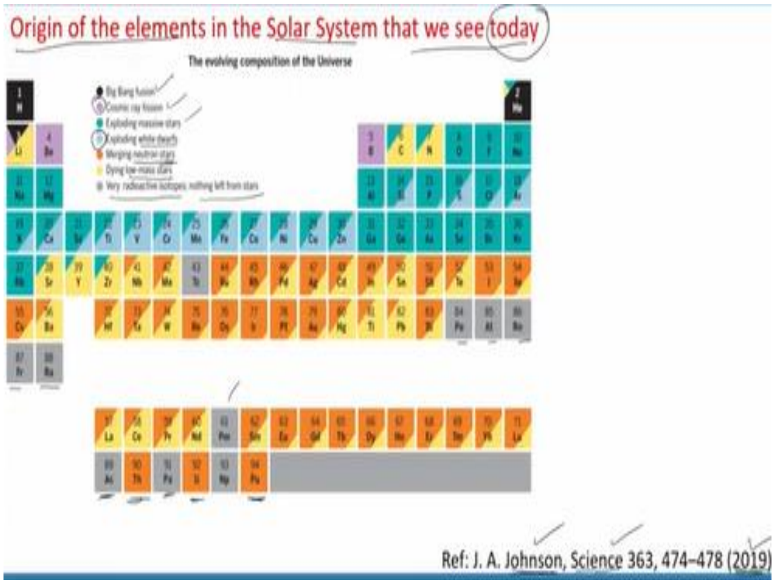
INTRODUCTION

Standard references for unfolding astrophysical processes in stars

Review of modern physics journal published in October 1957 synthesis of elements in stars by Burbidge, Burbidge, Fowler and Hoyle. So, this combination is well known as B^2FH. So, whenever you come across like B^2FH paper it means this is the one. You can see the contents elemental abundances and nuclear structure and physical processes involved in stellar synthesis, their place of occurrence, that means sites of these processes and what are the time scales associated with them. At this time independently AGW Cameron also published similar kind of paper titled as nuclear reactions in stars and nucleogenesis, which was published in June 1957. So, independently Cameron and B^2FH have published these papers on nuclear astrophysics that means mainly the cooking of elements in stars.

These papers remain standard references for understanding the astrophysical processes in stars. So, I strongly suggest you to go through these papers to understand how things evolved from 1957 regarding the subject of nuclear astrophysics in terms of research papers. Though there are many other papers in the field of nuclear astrophysics, I strongly suggest you to start with these two. You will get better idea about this field of nuclear astrophysics.

(Refer Slide Time: 10:18)



Origin of the elements in the Solar System that we see today

The evolving composition of the Universe

Ref: J. A. Johnson, Science 363, 474–478 (2019)

As I have given a paper from 1957, let me give you a recent paper published in 2019 by Johnson, I think this I have discussed in the previous lecture also published in science. So, this researcher has given a beautiful representation regarding origin of elements in the solar system that we see today. See H is completely shaded with pure black then He, most of it is black and then some other colours like yellow and green.

Now you see different elements are shaded with different colours. So, at this stage I want to only say one thing that the elements shaded with black are because of the big bang fusion. They were formed immediately after the big bang, three minutes after the big bang. Li, Be B most of them have been synthesized because of the cosmic rays.

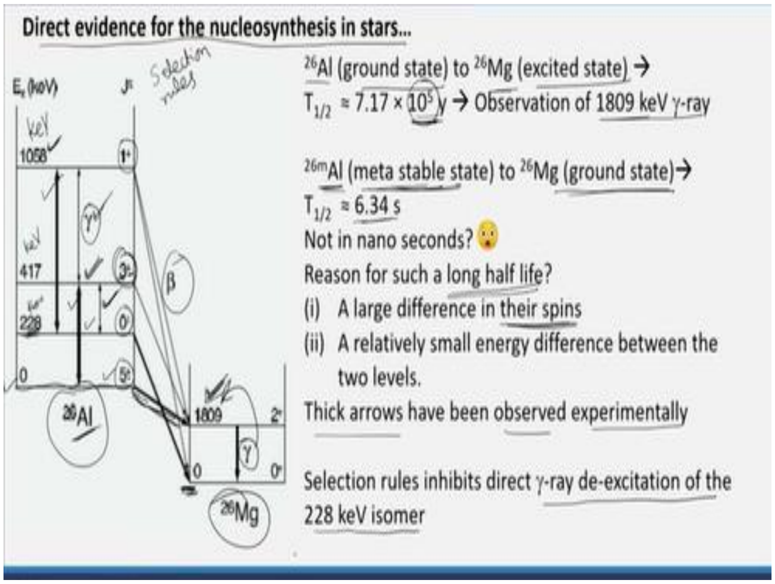
What are the cosmic rays made of? High energy protons. Then stars while evolving many times they will undergo explosion and because of exploding of massive stars that means stars, all the elements in this table some kind of periodic table shaded with green colour, were synthesized. Because of the explosion of some stars which are called as white dwarfs, the elements shared with this colour were synthesized. Then because of the emerging of the neutron star also many heavy elements are formed like in this table. You can see the elements shared with orange rubidium, rhodium, palladium, silver, cadmium all these elements.

And there are few elements which are formed only because of the merging of neutron stars that is thorium, uranium-92, plutonium-94. Now when low mass stars die then some elements are synthesized like lithium, carbon, nitrogen and all other elements which are shared with yellow colour also.

And very radioactive isotopes that means nothing left from the stars they were synthesized and those elements are called as Po, At, Rn, radon, francium and radium and this Pa, Pm, Ac. See the beauty of this table is to show what kinds of elements are formed from what kind of processes. So, in a nutshell this diagram gives you an idea about the reason for the synthesis of different elements.

After going through this paper published by Johnson published in science in the year 2019, I am sure you will enjoy. So, let us proceed.

(Refer Slide Time: 14:07)



Direct evidence for the nucleosynthesis in stars...

^{26}Al (ground state) to ^{26}Mg (excited state) →
$T_{1/2} \approx 7.17 \times 10^5$ y → Observation of 1809 keV γ-ray

^{26m}Al (meta stable state) to ^{26}Mg (ground state)→
$T_{1/2} \approx 6.34$ s
Not in nano seconds? 😮
Reason for such a long half life?
(i) A large difference in their spins
(ii) A relatively small energy difference between the two levels.
Thick arrows have been observed experimentally

Selection rules inhibits direct γ-ray de-excitation of the 228 keV isomer

Let me share another direct evidence for nucleosynthesis in stars. What was the faster direct evidence? Discovery of ^{99}Tc whose half-life is 2.2 lakh years. Do not get confused with the mass numbers of different isotopes. So, that discovery has you know changed the way people looked at the synthesis of elements in stars. Another discovery is ^{26}Al. What is so special about it?

Aluminium that we see in daily life, its mass number is 27, it is stable. Aluminium-26 is unstable, which was discovered by the researchers like technetium was discovered. It has some another type of story though in terms of discovery of an unstable isotope it is just like discovery of technetium. But aluminium has a different story I am sure you will enjoy the story of ^{26}Al. Before that, let me give you some basic information about the radioactive source by seeing which property of the radioactive source one can get the information about the source? With the help of what kind of photograph or what kind of image you can get an idea about the bones structure within a human being; it is x-ray scanning and you have MRI, CT screen. By seeing that photograph you can say what it looks like inside your human body and most of the information about the inside structure of the body can be extracted. Similarly, when a radioactive nucleus is given how to know what are the levels within the nucleus, what are their energies and with what type of radioactive decay the nucleus is trying to achieve stability. I repeat by seeing which kind of diagram you can get an idea about the energy levels of the radioactive isotope, half-life of the radioactive isotope and the type of nuclear radiation emitted during the decay? That diagram is called as energy level diagram. Sometimes we also use the word decay scheme or level scheme. Now I am going to show you the level scheme of ^{26}Al. Energy of first excited state is 228 keV, second exit state is 417 keV, third exit state is 1058 keV and the lowest one is the ground state. Nuclear level energy is not continuous, at least in the nucleus at the lower level they are in discrete. So, these discrete levels have some properties.

What are those properties? Each energy level has its own spin, it has its own parity. Now if you are not aware of the word spin and parity I will explain in separate lecture. If you are aware of this spin and parity then it will be easy for you to understand now. Otherwise, later when I explain you the concept of spin and parity then you come back to this and go through this lecture again.

So, spin and parity are the properties of the energy levels of the nucleus by which one can understand the transitions between the levels. Here in ^{26}Al decay scheme, if you see the ground state has spin parity 5^+ where 5 is the spin, + is the parity and the thick arrows denote the transition between 1058 keV and 228 keV states and 417 keV and ground state.

Corresponding to this only the experimental data is available. Now if you start from this 1058 keV, third excited state when it is decaying to 417 keV state, you see gamma rays there. This gamma ray can be detected, people have detected the gamma ray which is coming because of the transition from 1058 to 417 keV. The energy difference between these two levels is the gamma ray energy.

Now there is a possibility; in 417 to 228 keV, you see another transition is taking place, but no transition can take place from 228 keV to ground state. Why? Because from this 0^+ to 5^+ it is not possible for the transition to occur. Why? Because of the selection rules. If you have a BSc background and if you have been taught nuclear physics after plus two, I am sure you have been taught liquid drop model, then semi empirical mass formula and some of the disadvantages of this semi empirical mass formula were addressed by shell model. In shell model if you have learned you should know the meaning of this spin and parity and also the selection rules. Otherwise, go through any basic textbook of nuclear physics, it will be clear to you. So, the point which I am trying to convey here is following.

The transition is not possible from 228 keV to ground state, then what is going to happen? This 228 keV state, first excited state of ^{26}Al is going to the ground state of the ^{26}Mg. It is undergoing decay, because it is radioactive, it is not stable. However, the ground state of the ^{26}Al is unstable. So, because it is unstable it tries to reach to the stable state. How? By undergoing decay. Which decay? Beta minus.

The ground state of ^{26}Al is decaying to the 1809 keV which is the first excited state of the ^{26}Mg. The moment it is decaying to the 1809 keV of ^{26}Mg, immediately it will de-excite to the ground state by emitting gamma ray.

So, what is the energy of this gamma ray? Nothing but 1809 keV. Now keep this in mind and let me give you salient features of this decay scheme and how it can be direct evidence for the nucleosynthesis in stars which is very interesting. See decay from ^{26}Al ground state to exited state of ^{26}Mg is giving rise to 1809 keV gamma ray. The half-life of this decay is 7×10^5 years.

The 228 keV state in ^{26}Al is having relatively longer lifetime compared to other states, is a meta stable state, it has enough time to reach ground state of ^{26}Mg. Its half life is only six seconds. All other excited states in ^{26}Al are decaying to different states of ^{26}Mg and have half lives in the order of nano or pico or femtoseconds. The are not metastable states.

Excited states of some energy levels of a nucleus have long half-life which we are calling as metastable states because of two reasons. Number one if there is a huge difference in the spins; number two if there is a small energy difference between the two levels then also there is a possibility for having metastable state whose half-lives are not in nano or microseconds.

Anyway, another point in this diagram as I said thick arrows, have been observed experimentally not thin lines. Of course, they play important role in maintaining the equilibrium conditions within the stars, anyway that is not our business right now. See the selection rules inhibits as I said earlier the selection rules does not allow direct gamma-ray de-excitation of the to 228 keV isomer. It is because of the issue with the selection rules.

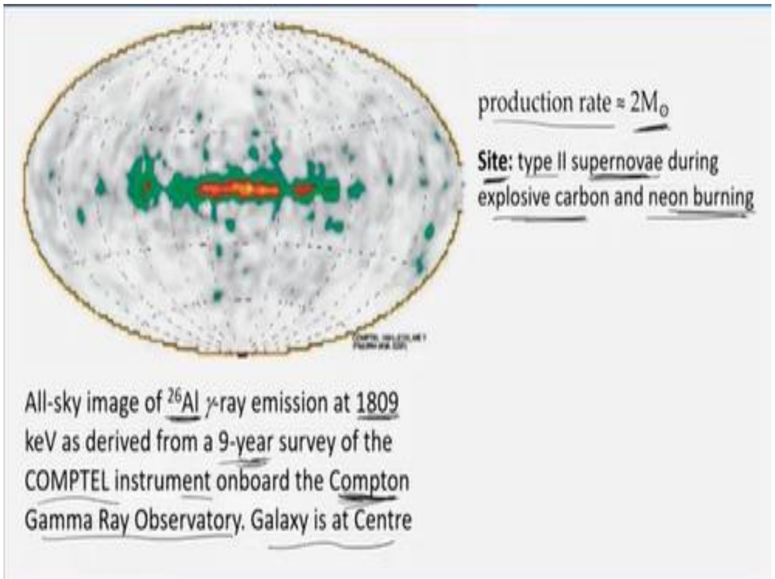
So, what it will do? It will decay to the ground state of ^{26}Mg. Now the actual point which I am going to highlight is following. People have detected 1809 keV gamma which is coming from the excited state to ground state of ^{26}Mg. Now a very important question you should ask if you are following what I am saying. Researchers have detected 1809 keV gamma, it is fine. Within the star nuclear reactions have taken place and they have formed ^{26}Mg as part of the nuclear reactions processes and maybe ^{26}Mg is formed in the first excited state and during the excitation within micro or nanoseconds it is giving 1809 keV. How is it possible to detect if this is the scenario? If magnesium is formed as part of nuclear reactions directly and magnesium is formed in the first excited state then whatever gamma is coming down with energy 1809 keV, that gamma ray would have absorbed within the star within no time.

It will not come out of the star because there is no time available. Now one interesting statement I am giving, at any place within the star when nuclear reaction is happening and gamma rays are emitting, those gamma rays are not coming out if the gamma rays are due to the transition from a nucleus which is formed in the nuclear reaction. So, gamma energy will be immediately absorbed within the star.

If it is absorbed within the star how we can detect on earth but we are detecting on the earth. What does it mean? This 1809 keV is not because of the population of ^{26}Mg but because of the decay of ^{26}Al ground state to exited state of ^{26}Mg. Why? Because this decay from the ground state of ^{26}Al is having half-life of 10^5 years. So, what? In 10^5 years, that means we have enough time for the gamma ray to escape from the star and reach the earth.

Are you getting what I am trying to say? ^{26}Al is decaying to the first excited state of ^{26}Mg whose half-life is 10^5 years and this time is sufficient for gamma ray to not get absorbed within the star always. It can always escape from the star and they can reach the earth. It is indeed reaching the earth and we are able to detect the gamma ray of 1809 keV. I really want to show one photographic evidence to support this statement.

(Refer Slide Time: 28:29)



production rate ≈ $2M_0$

Site: type II supernovae during explosive carbon and neon burning

All-sky image of ^{26}Al γ-ray emission at 1809 keV as derived from a 9-year survey of the COMPTEL instrument onboard the Compton Gamma Ray Observatory. Galaxy is at Centre

This is the all-sky image of ^{26}Al gamma emission at 1809 keV as derived from a 9-year survey. For nine years people have collected the data using COMPTEL instrument onboard the Compton gamma is observatory. So, Compton I think you may be aware, he is the one who proposes the way gamma ray interact with the matter that is a scattering process. So, in this picture galaxy is considered at the centre.

This green, yellow, red region show the existence of gamma ray of energy 1809 keV and this 1809 keV is the unique signal of ^{26}Al, nothing else. If you see the production rate of this gamma rays ^{26}Al interestingly it is about two times mass of the sun. And what is the site of this process? See throughout this course one has to explore or try to understand at which site this is happening.

Is it immediately after the big bang or within the star in the initial stage or the super supernova or in some other place? So, one has to look into the sites of various processes. So, that is what this course is all about. Not only the energy production in the stars not only the nucleosynthesis but also the sites of this nuclear processes is also interesting and important to understand. So, coming back to this the site of this ^{26}Al gamma ray is type 2 supernova during explosive carbon and neon burning. So, we have type 1 and type 2 supernova, which I will explain later. Basically, supernova is nothing but an explosion stage of the star at the end of the star.

Today's lecture is fully on the discovery of ^{26}Al and if you have not heard of decay scheme of a reductive source, I am sure you might have got some idea about the decay scheme of some source and especially ^{26}Al and how the transition is taking place from aluminium to magnesium and the half-life of the transition of the ^{26}Al ground state to the excited state of magnesium.

Half-life is around 1 million years and that time is sufficient for the gamma ray to escape the star and reach the earth and we are able to detect them. The conclusion is: because we are able to detect the gamma ray, that means synthesis is happening in the stars.

So, one million years before if something is happening and we are able to detect. That means the nucleosynthesis is a continuous process in the stars. It is still happening and at any time you can detect these lines of course, if you choose the experimental setup appropriately. Thank you very much for your attention and in the next lecture I will cover two more evidences of nucleosynthesis and then I will move on to the actual part of the nuclear astrophysics.

So, these are lectures in which astronomy that is observations and then explanation of the observations that is astrophysics I have been discussing. Thank you very much for your attention.