Nuclear Astrophysics

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

Lecture – 31
Charged Particle and Neutron Beams

Welcome students to today's lecture on general aspects of experimental nuclear astrophysics. Up to now in the course, you have seen different burning stages, different processes after the iron peaks; nuclear synthesis of elements beyond iron peak; silent features of the universe and; resonant and non-resonant reactions. So, all these topics were covered mostly from physics point of view.

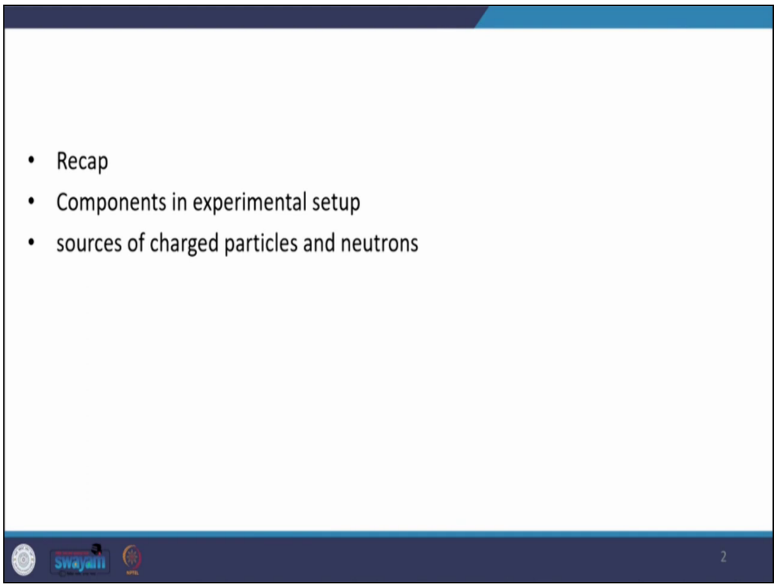
By now it is very clear that the chemical elements in the universe and the energy produced from the stars and different entities in the universe are because of nuclear reactions. What are the fingerprints of these nuclear reactions? It is the abundance curve along with many other features. So, one of the most important fingerprints in the universe for the nuclear reactions is the abundance curve.

But it is not sufficient to understand the speculations or the qualitative discussions only. It is also important to understand the quantitative aspects of the abundance curve. How do we understand the quantitative aspects of the abundance curve? We have to measure the nuclear reaction cross sections. You have to carry out nuclear reactions using different facilities available depending on your requirement and available resources.

In the last lecture we have seen s-process and r-process which are basically neutron induced radiative capture reactions. To understand the cross section behavior of this neutron induced capture reactions, you have to measure the gamma rays. We will discuss what are the experimental aspects involved those things in today's and upcoming lectures.

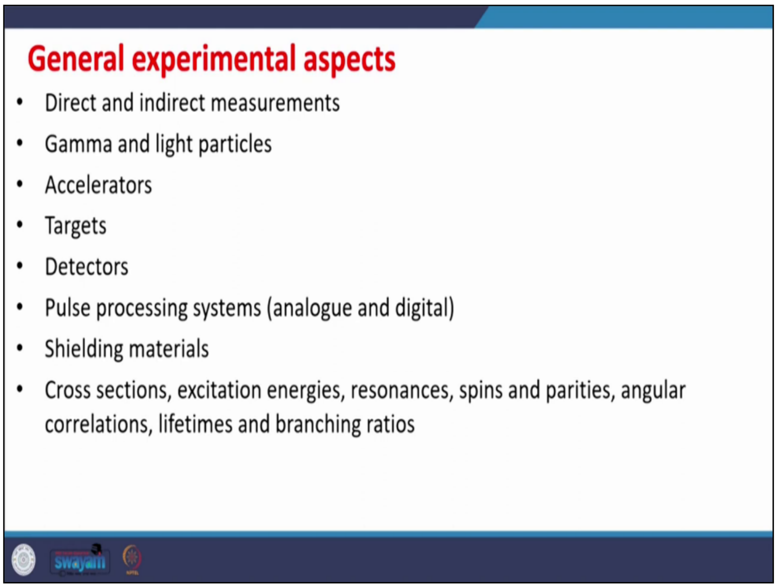
What was the summary of the previous class? We have seen the synthesis of elements beyond the iron peak because of the s-process and r-process. Very few elements; 35 nuclides, which are termed as excluded isotopes by Cameron, p-nuclei whose abundance is very low.

In today's lecture let me give you some information about the components that we normally use as part of experiments relevant for the nuclear astrophysics.



What are the components we have to have anyway? And then, what are the sources of the charged particles which are inducing the reactions for the synthesis of elements before the iron peak? What are the sources of neutrons, which have mass but no charge? How experimental measurements have to be carried out? What are the precautions?

In this course I will not go into the deep of these aspects but I will try to give you some kind of framework.



What are the general experimental aspects of nuclear astrophysics? We can divide the nuclear reactions relevant for nuclear astrophysics as two types of measurements: (1) direct measurement (2) indirect measurement. What do you mean by direct measurement? If you have the resources to carry out the reactions the way they are happening inside the stars in terms of flux, the number density of the nuclei involved in the reaction and the energies, then if we carry out those kinds of measurements, we call them as direct measurements. But there are challenges in carrying out the direct measurements. There are two important challenges.

(1) Extremely low cross section: Very low cross sections have to be measured and measurement of low cross section always invites problems from the uncertainty. You have to measure the cross sections with the available energies and then you have to extrapolate. The extrapolation always invites uncertainties.

(2) Many a times the nuclear reactions happening within the stars involve the unstable nuclides. It is impossible to prepare a target of unstable nuclei and do the nuclear reaction measurements.

So, it is because of one of these reasons why people go for the indirect measurements like charge exchange, particle transfer, scattering. For photo disintegrations, we need to use the gamma rays but the gamma sources are very rarely available on earth. So, you have to go for the indirect measurements. If the reactions are induced by gamma rays and light particles like protons electrons, then whatever reactions they induce in the stars also have to be measured using the available resources.

It is the accelerator for charged particles and also for neutrons indirectly. Accelerators have to be used to produce the beam of the particles to carry out the nuclear reactions. You have to have targets which should be stable throughout the nuclear reactions and thickness determination also plays very important role. Nuclear reaction will happen when the particle beam from the accelerator reacts with the nuclei in the target material.

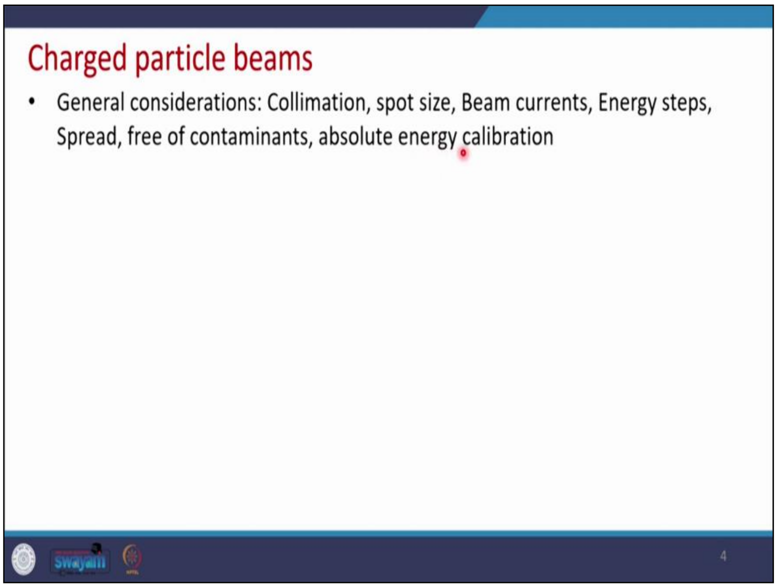
Because of the nuclear reactions, particles emitted mostly are gamma rays. You need to use detectors of high efficiency and very good resolution if you want to detect gamma rays, whose energies are closely separated from each other. Then you need to have pulse processing systems; either you can go for analog system or advanced digital data acquisition systems. Then you record the spectra or the pulses and analyze using some software. In general, when nuclear reaction happens, lot of unwanted radiation comes. The surroundings have to be shielded from the experimental setup. You should have appropriate and sufficient number of shielding materials surrounding the experimental setup. Otherwise, it can, not only harm the surrounding personnel, but also hamper the quality of the data obtained. What exactly do we measure from all these nuclear reactions which are relevant for the astrophysics? Of course, the fundamental quantity is reaction cross section. Many a times, we want to measure the excitation energy.

How do you measure the excitation energy of the nucleus after the reaction is formed? If it is having some resonance, what are the energy levels which are giving rise to the resonance? So, you have to measure the resonances also. Then, for each energy level of the compound nucleus, what are the spins and parities? And during the de-excitation from the excited state, whether more than one gamma ray or more than one particle are emitted.

Many times, researchers look forward to understanding the angular correlation between the particles emitted during the nuclear reactions. You have to use different detectors at the same time. You might have seen a source called as Cobalt-60 which emits gamma rays in cascade. The angle between these two gamma rays emitted from the cobalt 60 varies within a range. If you take Sodium-22 gamma source, it emits 511 keV gamma rays in opposite directions. You can study the angular correlation there also. You will see that maximum number of counts you get is when the angle is 180° between the two gamma rays. We might want to measure the lifetimes of these nuclear levels and the branching ratios also.

So, all these parameters we need to measure in order to understand the synthesis happening within the stars and in the universe. These are the important components of any nuclear reactions relevant for astrophysics. If you do not have any facility, just go for a theoretical aspect. But we need to have an idea about the experimental aspect of the nuclear astrophysics as well.

Let us start with the charged particle beams. What are the general considerations for the charged particle beams?



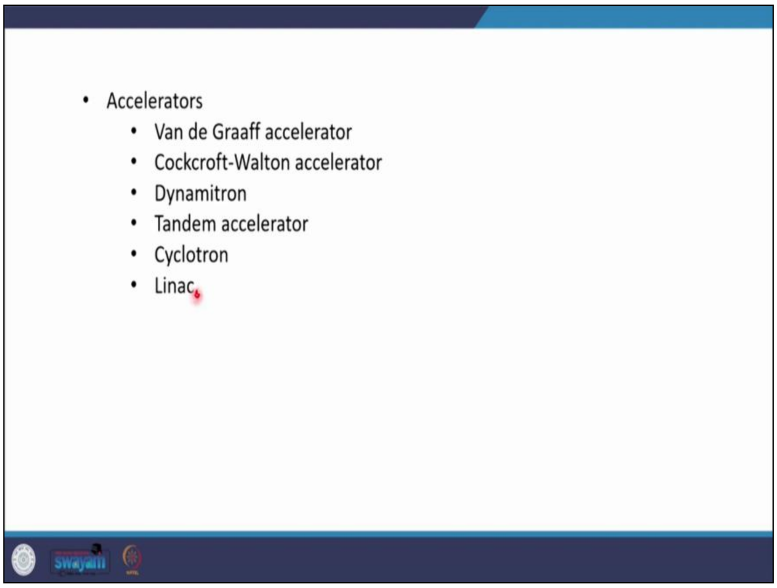
The particle beam coming from the particle accelerator has to be collimated well. Otherwise, instead of falling on the target material, it can fall on the material surrounding the target and it can give you unwanted radiation. So, the collimation plays very important role which can be achieved by using magnetic slits and using various methods within the accelerator. You have to ensure that beam is exactly falling on the target material. The spot size has to be decided so that it covers the target material. So, the spot size diameter should be less than the area of the front surface of the target material. This is where beam optics comes into picture.

Should beam current be less or more to carry out the nuclear reaction relevant for the astrophysics? Remember we are dealing with nuclear reactions having very low cross section. So, for accurate measurement of the cross section, you need large number of incident particles. Since cross section is already very low, if the beam current is also low, then the ejected particles will be less, and the statistical fluctuation will be more and it will lead to the uncertainty in the measurements. So, more current is, in general, preferred for the measurement of nuclear reactions.

In what steps you have to change the energy? If you are interested in finding out the resonances closely separated from each other, then the energy step should be very small. In this, normally we go for 100 eV. Sometimes we can increase the energy steps depending on the energy level diagram. But small value of energy step is better for getting the information related to the resonance phenomenon.

The spread of the incident particle beam should be less and we normally prefer that it should be in the order of electron volts. More spread leads to more spread in the cross section values. when we want to have nuclear reaction which is happening in the stars at a particular energy, even if there is a small spread around the center of the Gamow peak and if there is a spread in the instant particle beam then the data you are acquiring will be of very bad quality.

The target also should be free of the contaminants. The absolute energy calibration of the particle accelerator is very important. We will discuss the methods of this energy calibration and the reactions which are useful.

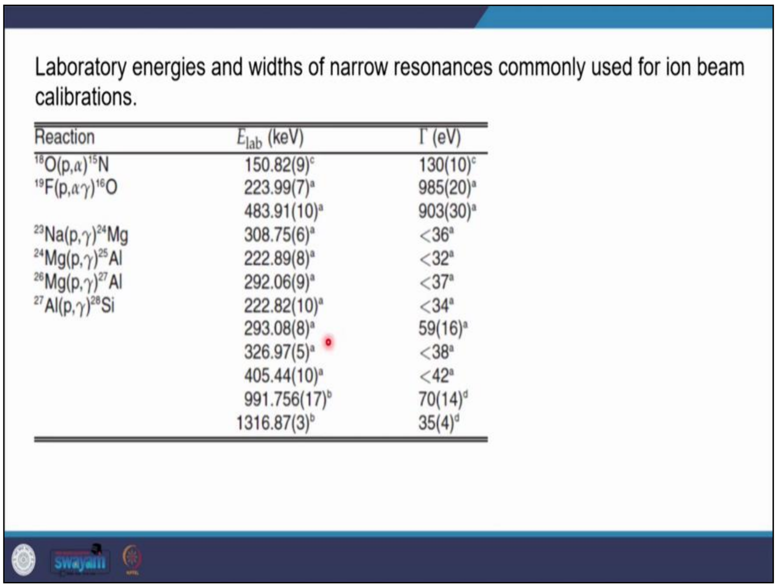


We come across different kinds of accelerators. You are aware of van de Graaff generator for relatively less energy of the proton beams. One can go for the initial version of the linear accelerator, i.e., Cockroft-Walton accelerator. One can go for a Dynamitron. One can go for tandem accelerator and one can go for the cyclotron for compact size. And we can also use synchrotron which is an extended version of the cyclotron.

The details of these accelerators are available in many textbooks. So, you are suggested to go through those textbooks and read them, so that you can understand the basic principle of all these accelerators. In the linear accelerator, the basic principle is acceleration of the particle in the presence of electric field. In the case of cyclotron, magnetic field is used to allow the electrons to follow the spiral path and also electric field for the accelerations. If magnetic field is changing with respect to time, we call it as Synchrotron.

Linear accelerator, which produces more energy for the charged particles, uses the different steps of accelerators. In India, we have one Linac in TIFR and people are successfully doing the experiments using this Linac facility.

Where is this Linac facility important in: direct or indirect measurement? Linac produces high energy particles, but that much high energy is not involved in the stars. So, understanding direct measurements are not possible using Linac. Linac is highly preferred for indirect measurements.



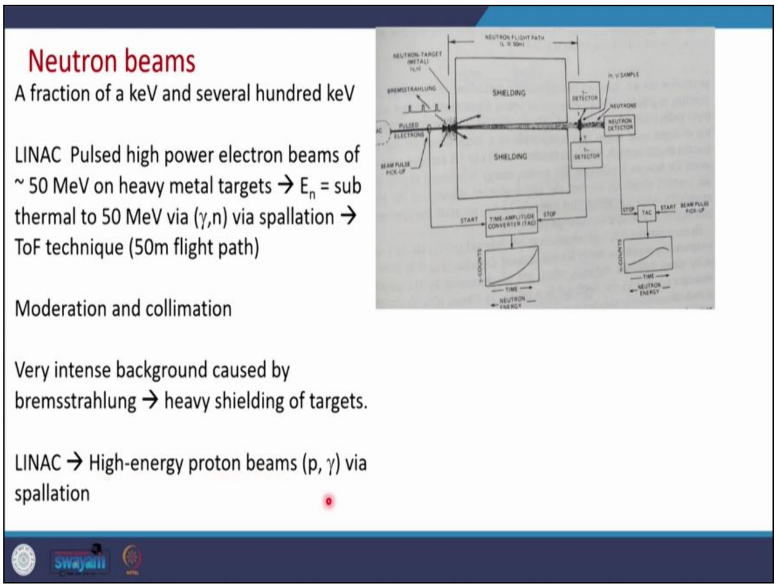
Laboratory energies and widths of narrow resonances commonly used for ion beam calibrations.

Reaction	E_{lab} (keV)	Γ (eV)
$^{18}O(p,\alpha)^{15}N$	150.82(9)[c]	130(10)[c]
$^{19}F(p,\alpha\gamma)^{16}O$	223.99(7)[a]	985(20)[a]
	483.91(10)[a]	903(30)[a]
$^{23}Na(p,\gamma)^{24}Mg$	308.75(6)[a]	<36[a]
$^{24}Mg(p,\gamma)^{25}Al$	222.89(8)[a]	<32[a]
$^{26}Mg(p,\gamma)^{27}Al$	292.06(9)[a]	<37[a]
$^{27}Al(p,\gamma)^{28}Si$	222.82(10)[a]	<34[a]
	293.08(8)[a]	59(16)[a]
	326.97(5)[a]	<38[a]
	405.44(10)[a]	<42[a]
	991.756(17)[b]	70(14)[d]
	1316.87(3)[b]	35(4)[d]

These are some reactions, laboratories energies, and widths of the narrow resonances which we use for the ion beam calibrations.

You see Aluminum-27 which is a widely used reaction because you have different energies. Even one reaction is sufficient for ion beam calibration. Aluminum 27 is widely available and you see the width in electron volt. So, for the calibration of ion beams, we have to carry out these kinds of reactions first and then you go for the reaction of your interest to study the nuclear astrophysics.

So, this table shows a compilation of laboratory energies, not centre of mass energies, and widths of the narrow resonances.



Coming to neutron beams now. Linac is widely used for the production of neutrons. So, in this beautiful experiment shown in figure, let me explain how it works. A pulsed high energy electron beam is used to produce neutrons, whose energies are from a fraction of keV to several hundred keV, of course, after moderation.

When we allow linac pulsed high power electron beams, whose energy is 50 MeV, to fall on the target material, then neutrons are produced by a spallation reaction. Spallation reaction is a violent reaction in which a target is bombarded with very high energy particles, in this case, electrons. The incident particle denigrates the nucleus through inelastic nuclear collisions, and it involves the breaking up of the target nuclei into several constituents. The result is emission of protons, neutrons, alpha and other particles. Neutrons produced in these kinds of reactions can be extracted and used in experiments. The number of neutrons produced here depends on the type of target material and the energy of the incident particles. In general, the target material in the spallation sources are high Z materials; like lead, tungsten, silver and bismuth.

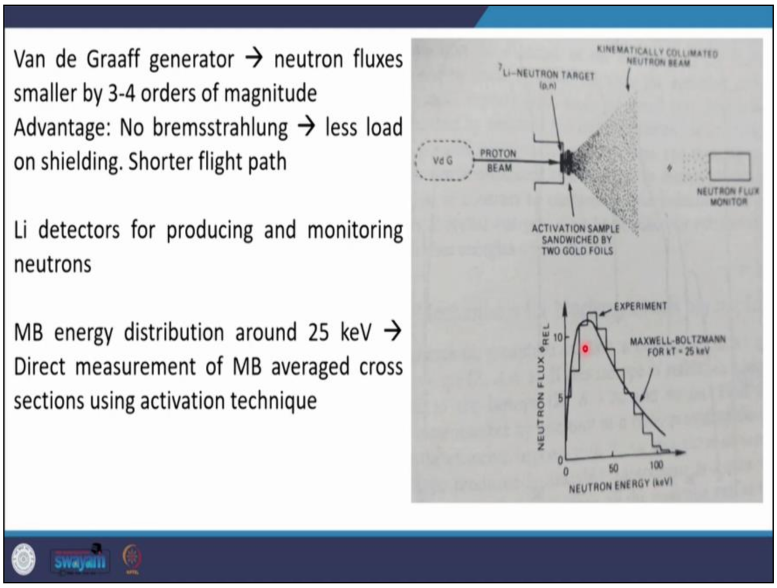
Fragments and neutrons are produced in fission reactions also. What is the difference between spallation and fission reaction? The basic difference is: neutrons produced in fission reaction can initiate further fission and that is the basic principle of nuclear reactor, whereas, in spallation reaction, the neutrons produced in the primary reaction cannot initiate another spallation reaction.

Spallation kind of reaction can be assumed when proton reacts with lithium because it is also source of neutrons.

So, one can produce neutrons by allowing the charged particles fall on heavy metal target or one can produce neutrons by allowing the protons or electrons on a target material.

You can see high level of shielding is arranged here. Normally we use concrete material for the shielding of neutrons. When these neutrons interact with the target material which is inducing capture reaction, gamma rays have to be detected by using detectors. It could be semiconductor detector like high purity germanium or scintillation detector like lanthanum bromide or sodium iodide detector. Depending on the application, you use one or more detectors.

Neutron detector also can be placed here to monitor the neutrons which are coming from this primary target material. Heavy shielding of targets is required because of the very intense background due to Bremsstrahlung. This process is a very important consideration in these nuclear reactions. Bremsstrahlung is one of the processes by which, not only in this kind of nuclear reactions but in the nature also, cosmic rays from the space dissipate some of their energy in the earth's atmosphere. Solar X-rays have been attributed to bremsstrahlung, generated by fast electrons passing through the matter in the part of the sun's atmosphere which we call as chromosphere. Internal bremsstrahlung also arises in the radioactive disintegration of the beta decay, which consists of production and emission of electrons by unstable nuclei. These electrons deflected in the vicinity of their own associated nuclei, emit internal bremsstrahlung. So, within the high electric field of the nucleus, the electrons undergoes bremsstrahlung process.



To reduce the shielding material, we use Van de Graaff generator. Though neutron flux is less by 3 to 4 orders of magnitude, we can reduce the burden on the shielding material. Plus point is that, there is no bremsstrahlung. Flight path is also less. In the previous diagram, the flight path is 50 meters. So, here we are using timer flight technique which I will discuss in detail in upcoming lectures.

This time of flight technique is normally preferred considering the light path taken by the gamma ray, which travels with the speed of light and neutron velocity, of course, it travels with velocity less than the speed of light. That is how this flight path is defined. Depending on the energy, one can have a control over the angle with which neutrons are emitted. Lithium detectors are used for producing and for monitoring the neutrons. As I said, protons plus lithium-7 gives rise to beryllium and neutrons. And if you allow proton to fall on the beryllium-8, it gives boron-9 and neutron is produced. Here, I am also using neutron flux monitor, so that I know what number of neutrons is emitted in the reaction.

We always prefer to have the precise energy distribution of the thermal neutrons after the moderation. This is about 25keV in this beautiful experiment and the direct measurement of the Maxwell Boltzmann average cross sections. We prefer activation technique here, instead of time-of-flight technique, whose details I will discuss in upcoming lectures.

With this I will close today's lecture. To quickly summarize today's lecture, I have discussed important components which are required to carry out nuclear reactions relevant for the nuclear astrophysics, some considerations for the particle beams, how to produce the charged particles using different accelerators and how to produce the neutrons. And only after thermalizing them, we can carry out the nuclear reactions. Otherwise, those neutrons energies are very high whereas energies are very less in the stars. Using the moderators of sufficient thickness is also very important. I will discuss many more aspects of detectors and targets in upcoming lectures. Thank you so much for your attention.