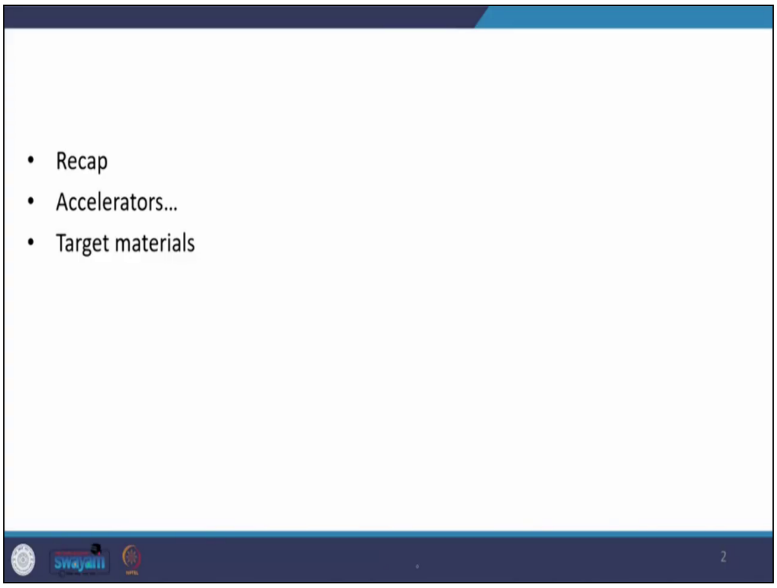
**Nuclear Astrophysics**
**Prof. Anil Kumar Gourishetty**
**Department of Physics**
**Indian Institute of Technology – Roorkee**

**Lecture – 32**
**Accelerators and Targets**

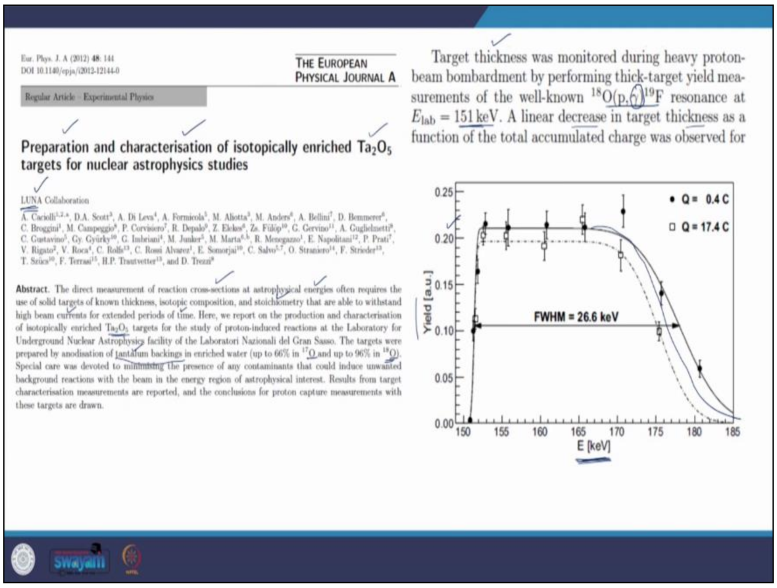
Hello to everyone. In the last class, I discussed the considerations regarding particle beam. Basically, we are discussing the experimental aspects of nuclear astrophysics. We have seen how many types of accelerators are there and what should be the considerations regarding the particle beam and how charged particles and neutrons can be generated.

In today's lecture, we will see one problem which discusses the effect of small shift in the particle beam’s energy on the cross sections of the nuclear reaction. By now, it must be clear to you that any experiment related to nuclear astrophysics are basically centered around the measurement of cross section, because it is the cross section of the nuclear reaction which gives the information about the rate of the nuclear reaction by taking its product with the velocity. From the reaction rates, researchers find the abundance evolution. The energy production in the star, its lifetime, etc. can be analyzed from the cross section. Though Q values are sufficient to find out the energy emitted from a nuclear reaction. So, the center of the discussion on experimental aspects of nuclear astrophysics is the measurement of cross-section.

Will there be any change on the measurement of cross-section if there is a slight change in the accelerator beam energy? We will discuss through one numerical. After that, we will discuss another important aspect of the experimental nuclear astrophysics, i.e., target materials. In the star, when nuclear reactions are happening, there is nothing like projector and target. It does not matter which one is projectile and which one is target. But can we create that kind of situation in earth's laboratory? No. You have to perform nuclear reactions using particle accelerator. After particle accelerator, the second important component in the nuclear astrophysics is target materials. In today's lecture, we will see what are the target materials and associated equipment which we should understand before planning for any experiment.




The backing materials, target chambers and the target holders, all these things come under the targets. Let me discuss the problem related to the measurement of cross section when there is a change in the particle beam energy. Let me show you one interesting paper which I have came across.




This paper is from one of the important experimental facilities in the world: LUNA, Low Energy Underground Laboratory for Nuclear Astrophysics laboratory to carry out the experiments related to nuclear astrophysics. LUNA collaboration has come up with wonderful experiments and they reported data related to lot of nuclear reactions relevant for nuclear astrophysics.

In this particular paper you can see preparation and characterization of isotopically enriched tantalum oxide target for nuclear astrophysics studies. They have measured the cross sections at astrophysical energies which often requires the use of solid targets of known thickness, the composition of isotopes, the stoichiometry, which is one of the main challenges. I will discuss the role of stoichiometry of target material also.

When you consider any target material, it should withstand high beam currents for extended periods of time so that you get enough data. You need to take the data for a long time in order to reduce the statistical uncertainty. They have reported on the production and characterization of some tantalum oxide target for the study of proton induced reactions in the laboratory for underground nuclear astrophysics. It is placed in Gran Sasso. Here, the targets are prepared by anodization of tantalum backings. Why Tantalum is preferred over other materials? I will discuss.

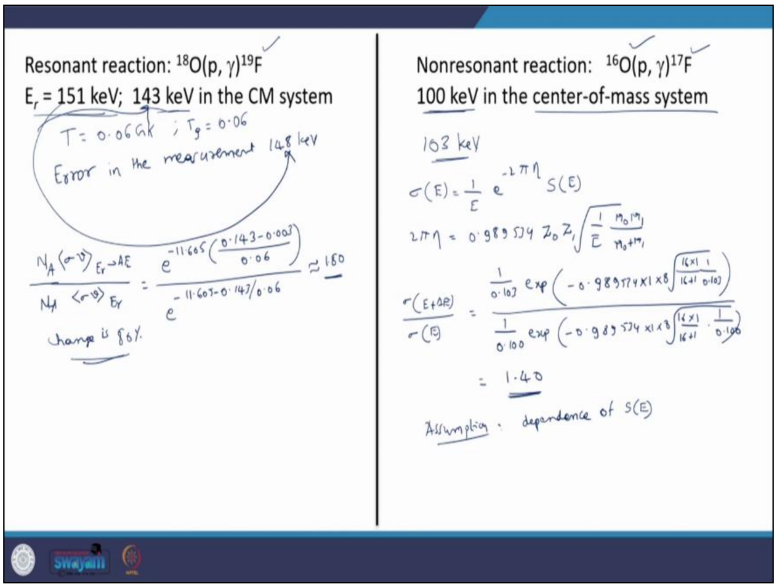
Anodizing is done in enriched water (up to 66% in oxygen 17 and 96% in oxygen 18). So, it is clear that incident beam is proton, and the target material is oxygen.

When they measured the cross section, the target thickness was monitored during this heavy proton beam bombardment by performing thick target yield measurements of the well-known resonance at laboratory range of 151 keV. You have to ensure whether the thickness of the target is changing or not. What will happen if the target thickness changes.

Of course, there is a huge change in the yield and after some time it can evaporate as well. So, when you consider a nuclear reaction, it is important to monitor the thickness using various methods. You can calculate the Q value of this reaction, which gives you the energy of the resonance in the fluorine 19.

They have observed a linear decrease in thickness as a function of the total accumulated charge. In the figure above, energy is on the x axis and yield is on the y axis. It is almost constant around at 0.21. After, say, 165 keV, the yield is decreasing. Why is it happening? The decrease in the yield of a nuclear reaction shows that the target thickness is changing.

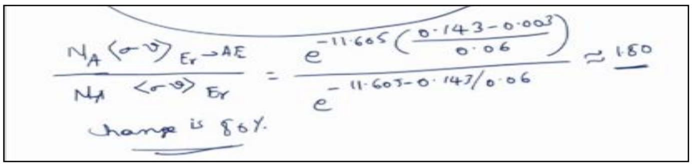
So, you have to see, after which laboratory energy, the thickness is undergoing a change. When I say yield, I mean the yield of the gamma rays emitted when proton interacts with oxygen. The lab energy at this time is 151 keV. This is one method which shows how to monitor the target thickness all.




Let me consider the resonance energy 151 keV and 143 keV in CM system. The aim of this discussion is to see the change in the cross sections of the nuclear reactions when there is a slight change in the energy of the projectile.

I am looking for the resonance at 151 keV. Consider the temperature at 0.06 GK or $T_9$=0.06, both are same. Remember, whenever you perform a nuclear reaction experiment, you have to quote the corresponding temperature as well. Because you have seen the impact of temperature on the performance of any nuclear reaction many times.

If there is an error in the measurement of, say, 3 keV in the resonance energy, we are reporting it as 148 keV. Then, what will be the change in the cross section?




So, for a slight change in the projectile energy, say by 3 keV, the change is about 80%. So, you can imagine the accuracy with which the measurement has to be carried out.

Now let us see the non-resonant reaction. By now it must be clear to you what is the difference between resonant and non-resonant reaction? Whenever I say resonant reaction is analyzed, one has to mention the energy of the resonant state, whereas, in the case of non-resonant reaction it is sufficient to mention the projectile energy because non-resonant reactions, in general, happens with all incident projectile energies.

Now what if the non-resonant reaction between proton and oxygen is considered? Here the compound nucleus is F 17 and the projectile energy is 100 keV in center of mass system. Instead of 100 keV, what will happen if I perform it at 103 keV?

The cross section for a non-resonant reaction is:

$$\sigma(E) = \frac{1}{E} e^{-2\pi\eta} S(E)$$

$$2\pi\eta = 0.989534 \, Z_0 Z_1 \sqrt{\frac{1}{E} \frac{m_0 m_1}{m_0 + m_1}}$$

$$\frac{\sigma(E+\Delta E)}{\sigma(E)} = \frac{\frac{1}{0.103} \exp\left(-0.989534 \times 1 \times 8 \sqrt{\frac{16 \times 1}{16+1} \cdot \frac{1}{0.103}}\right)}{\frac{1}{0.100} \exp\left(-0.989534 \times 1 \times 8 \sqrt{\frac{16 \times 1}{16+1} \cdot \frac{1}{0.100}}\right)}$$

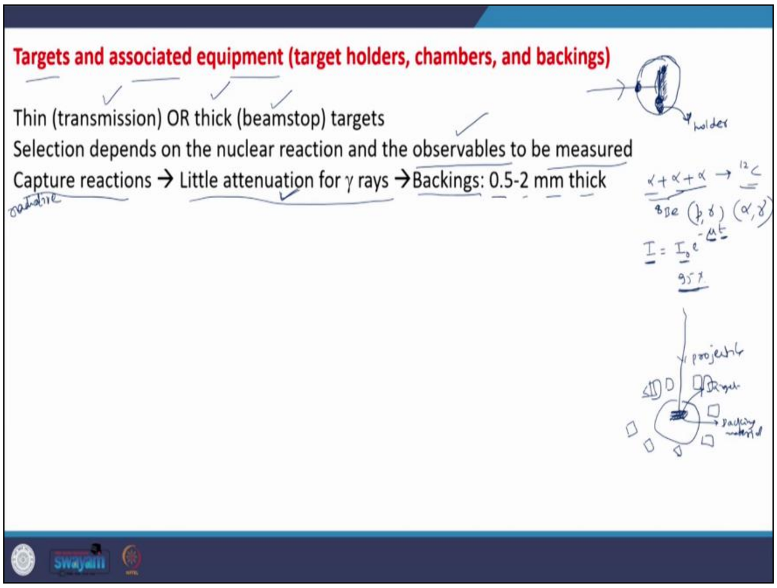
$$= 1.40$$

Assumption: dependence of S(E)

So, change in the projectile energy by 3 keV has resulted in 40% change in the cross section of the nuclear reaction. In case of resonant reaction, it was about 80%. In case of non-resonant reaction, it is about 40% just by changing the projector energy by a few keV. So, it is very important to ensure the accuracy in the projectile energy, especially for charged particle induced reactions.

This example must have cleared the role of accuracy in the projectile energy while measuring the cross sections. Remember, one of the important assumption which has been made is the dependence of S-factor.

You can read textbooks like Cauldrons in the Cosmos by Rodney and Rolls and the introduction to nuclear physics in the stars by Illiadis for more details.



Let us go to the next topic, i.e., targets and associated equipment. The two main goals of nuclear astrophysics course are understanding the energy production in stars and synthesis of elements in the universe. So, of course, it is very important to perform nuclear reactions in earth's laboratory using particle accelerator. We cannot create an environment where a nucleus undergoes reaction with each other without considering the projector and target concept, like in stars.

Until now, we discussed particle accelerator which takes care of the projectiles and now let me provide a brief overview of the targets. When I say target, I am not confining to only the target with which the projectile is reacting. I am also including the associated equipment. When a particle beam falls on any target, you cannot just hold the target in air. You should have a chamber. You should place target above some target holder. Then, you should have some kind of backings. Many a times, it is important to have a supporting material for the target to stay there during the nuclear reaction, which we are calling as backings.

What are the considerations related to these targets and associated equipment? The discussion on target materials is centered on charged particle induced reactions ,which play important role for the energy production in stars and synthesis of elimination stars before the iron; and neutron-induced reactions which play a role in the energy production in stars and synthesis of elements via s-process and r-process, that is, beyond ion peak.

Let me start the important considerations of the targets and associated equipment. Of course, it depends on the thickness of the target material. Depending on the nuclear reaction of interest either one can go for a thickness of target which is such that ion beam can pass through the target material.

The thickness is thin enough such that ion beam passes through the material. Sometimes, depending on the nuclear reaction of interest, the thickness is such that beam is completely stopped within the target material.

I have given names: beam stop target and a transmission target. The synonym for transmission target is thin target and beam stop target is thick target, though thin and thick are relative.

Selection of target also depends on the observables to be measured. Consider the triple alpha reaction. It is a two-step process. If we want to measure the cross section, then the carbon 12 has to get disintegrated into three alpha particles. Accordingly, the detectors have to be chosen. Even the target materials should be designed in such a way that alpha particles do not lose much energy within the target material. If you want to measure the gamma energy, then accordingly, target thickness can be considered. If you want to measure the scattered projectile, accordingly, the target material has to be chosen.

Consider one of the major reaction type that we come across in nuclear physics: capture reactions. When I say capture reaction, it could be induced by neutrons or protons. Capture reactions can be further divided into radiative capture and non-radiative capture. Radiative capture reaction means the ejectile is gamma. If you consider $(p,\gamma)$ or $(\alpha,\gamma)$reaction, the target should be in such a way that there is very little attenuation for the gamma rays.
Considering this, normally, the backing materials are chosen such that the thickness is in between 0.5 to 2 millimeter thickness. The thickness of the backing material should be in such a way that there should be little attenuation of the gamma rays. If there is a huge attenuation, we are losing lot of gamma rays and the count rate in the nuclear reactions will be less. There is a beautiful advantage when the thickness of the backing material for the target material is chosen in such a way that there is above 95% transmission for the gamma rays.
Little attenuation in this backing material allows detectors to be placed at any place, so that we can get large number of counts.

So, these are some of the important considerations for the backing materials when we discuss the target materials. We will see more about the target materials and preparations of the backing materials and chambers and target holders and the arrangements to be done in the next lecture. Thank you very much.