Nuclear Astrophysics

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Lecture – 33

Backing materials and Target preparation

Welcome to today's lecture which is a continuation of previous lecture in which I have discussed an example to highlight the effect of slight change in the particle beam energy on the cross-section measurement. You have seen for the resonant reaction it was about 80% when proton interacts with oxygen-18 and for non-resonant nuclear reaction for proton and oxygen 16 we have seen the change is about 40% in the cross-section measurement.

So, it is very important to calibrate the particle beam energy. Then we have seen a few considerations for the targets and associated equipment. As part of that I have been discussing the considerations of backing materials and the thickness of the backing materials as I have said it is between 0.5 to 2 millimeters considering radiative capture reactions it could be alpha gamma it could be p gamma it could be neutron gamma anything.

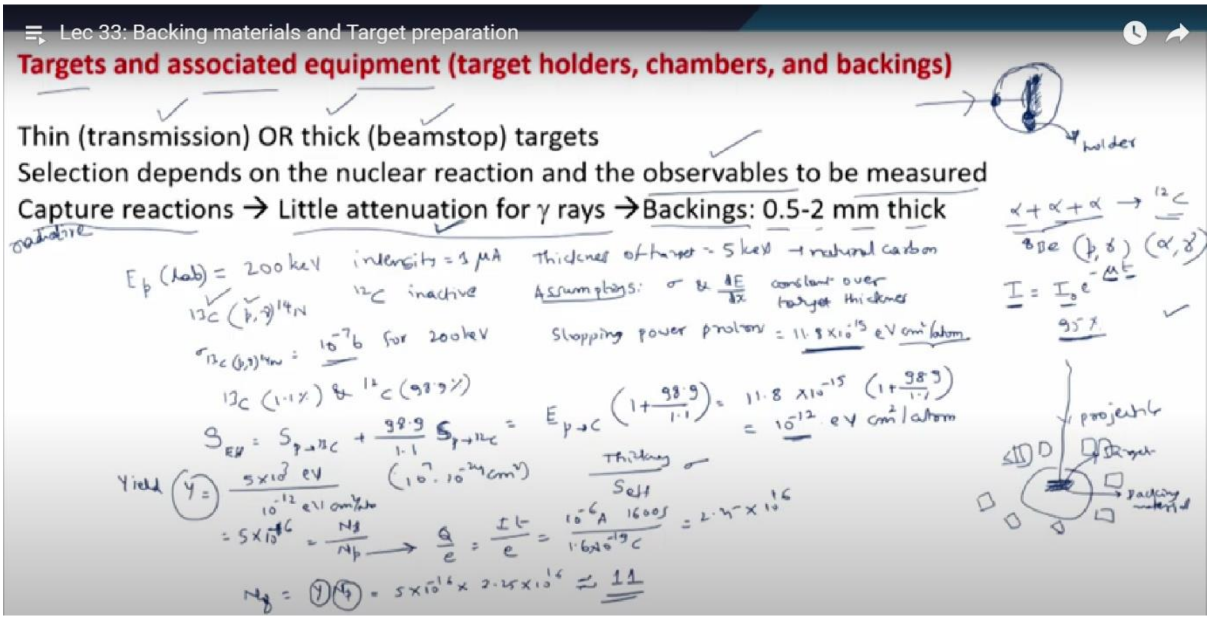
But if the ejectile is a gamma ray the backing material if at all it is required in general it is very much required it should be in such a way that the transmission of gamma rays should not be affected much as I said 0.5 mm thickness leads to the transmission of about 90% of gamma rays if the gamma energy is low and if the gamma energy is high then it is about 95% and we have seen we can categorize the target materials into two types that is transmission and beam stop.

Transmission means the thickness is thin enough that ion beam pass through the target material. And in case of a beam stop target material thickness is chosen in such a way that whatever beam we are considering it will be stopped within the target materials. So, when you say thick or beam stop material that is what is the meaning. Now so, we are considering projectile and target materials and most of the reactions are radiative capture reactions in stars.

So, let us try to discuss one numerical to find out the number of gamma rays emitted in a nuclear reaction. We will see so, many parameters comes into picture when we try to calculate the number of gamma rays emitted during a nuclear reaction. So, you need to consider the efficiency of the detector you need to consider the proton beam incident current and then energy.

So, there are so, many parameters which comes into picture and finally we need to find out the number of gamma rays emitted in a nuclear reaction. So, let us see proton induced reactions with carbon and the given information is following.

So, a beam of singly charged protons the laboratory energy of protons. One has to clearly specify whenever anyone uses the energy of the projectile whether it is given in centre of mass frame of reference or laboratory frame of reference and conversion of quantities between these two frames of reference should be known to you. So, this proton beam energy say it is 200 keV and say intensity of this proton beam is one microampere.



I am giving the intensity of the beam in terms of current 1 micro ampere and thickness of the target is 5 keV. What is the reaction material 13C p gamma 14 N. Basically I am using a natural target natural carbon target whose thickness neither I am giving in terms of micrometers nanometers nor in terms of grams per centimeter square but I am giving in terms of energy. What does it mean?

The energy loss of the protons when I say loss of energy the instant energy is say 200 keV and the thickness of the target is chosen in such a way that when proton beam passes through this target material of course it is a transmission target it is about 5 keV. So, the reactions have to happen within this 5 keV difference that we have to keep it in mind and current is given like 1 microampere reaction is proton and carbon 13 in the natural carbon you have both carbon 12 and carbon 13.

But here I am trying to understand the proton on carbon 13 reaction. So, you can assume that 12C carbon which is present in the natural carbon target is inactive. So, there are few assumptions you have to take number one cross section and also stopping power dE by dx they are approximately constant over target thickness. And the given cross-section for this carbon p gamma 14 N is 10 to the power of -7 barn.

Remember the cross section is a strong dependent of energy. So, when I am giving here the cross-section value it is meant for 200 keV laboratory energy and the cross section is 10 to the power of -7 barns that means how much 100 nano barn. See the values of cross sections of nuclear reactions are relevant for nuclear astrophysics. So, as I said repeatedly in several lectures it is one of the challenging aspect.

Low cross section leads to lot of complications in the planning of experiments relevant for nuclear astrophysics. And if I give you stopping power of protons when I say stopping power what does it mean see this requires the background of interaction of charge particle with matter.

We know neutrons being charge less but having mass it will interact via scattering and absorption.

Gamma rays being chargeless and massless they interact via photoelectric, Compton and pair production and charged particles like electron beam proton beam alpha beam and heavy ion beam they interact by a coulomb process. So, it is basically ionization and excitation and what is the energy loss per unit length that is the stopping power of charged particle within the matter. So, it requires an understanding of interaction of radiation with matter. So, here the stopping power of protons is given as 11.8 into 10 to the power of -15 electron volt centimeter square per atom.

So, if you multiply with the number of atoms per number density of the atoms you can see what kind of unit we will get. So, given this information what is the number of gamma rays emitted that we need to calculate. So, let us see remember this target contains both carbon 12 and carbon 13 but reaction is taking place only with the carbon 13. Then you need to consider the effective stopping power right. So, what is the effective stopping power let us see.

So, 13 carbon is 1.1% and carbon 12 is 98.9% nuclei. Now the stopping power of protons both in carbon 12 and carbon 13 there is not much different there is no much difference. So, we have to assume that stopping power of proton in carbon 12 and carbon 13 it is same. Under this consideration what is the effective stopping power. So, stopping power S effective if you consider it is basically stopping power for proton on 13 carbon plus see 98.9% of carbon 12 is there right and 1.1 is carbon 13.

So, this is effective stopping power for proton on 12 carbon. So, effective stopping power for proton on natural carbon is given as 98.9 divided by 1.1. So, this gives me 11.8 is already given here the stopping power of protons into 10 to the power of -15 and 1 plus 98.9 by 1.1 if I calculate this it will be like 10 to the power of -12 electron volt centimeter square per atom.

Is there any difference? Yes. See 10 to the power of -15 is there for the stopping power of protons but effective stopping power is of the order of 10 to the power of -12 knowing this what is the next step it is the calculation of yield is equal to the thickness of the target that is 5 into 10 to the power of 3 electron volt divided by 10 to the power of minus effective stopping power electron volt centimeter square by atom 10 to the power of 7 into 10 to the power of -24.

Basically what I have done is the thickness of target divided by effective stopping power into sigma I have taken the cross section is not it. So, what is the yield of the nuclear reaction multiply the cross section with the effective stopping power and multiply the thickness and divide with the effective stopping power all right and when you do this calculation it gives me 5 into 10 to the power of -16.

And this yield is nothing but number of gamma rays emitted and the number of protons falling on the target material. Now how to find out this Np simple you know the current given is one microampere. One microampere corresponds to number of protons it is simple by taking the consideration of charge. So, it is basically Q by e and what is q current into time divided by e and 10 to the power of -6 ampere.

And for one hour the reaction takes place. So, 1600 seconds divided by 10 to the power of -19 coulomb charge of each a charge sort of 2 into the power of mine to 2.25 to the power of 16.

So, the total number of gamma rays emitted is yield into number of protons that is 5 into 10 to the power of -16 into 2.25 into 10 to the power of 16 this is about 11. So, what exactly we have done here the current is given.

So, incident projectile beam the current is given convert into the number of protons by knowing the irradiation time. So, for how long the beam is falling on the target material that one has to get. So, here it is one hour. So, once you get the N p number of protons and yield from the effective stopping power cross section and the thickness N gamma can be easily calculated. See number of gamma is emitted number of protons falling on the target material that is the yield of the nuclear reaction.

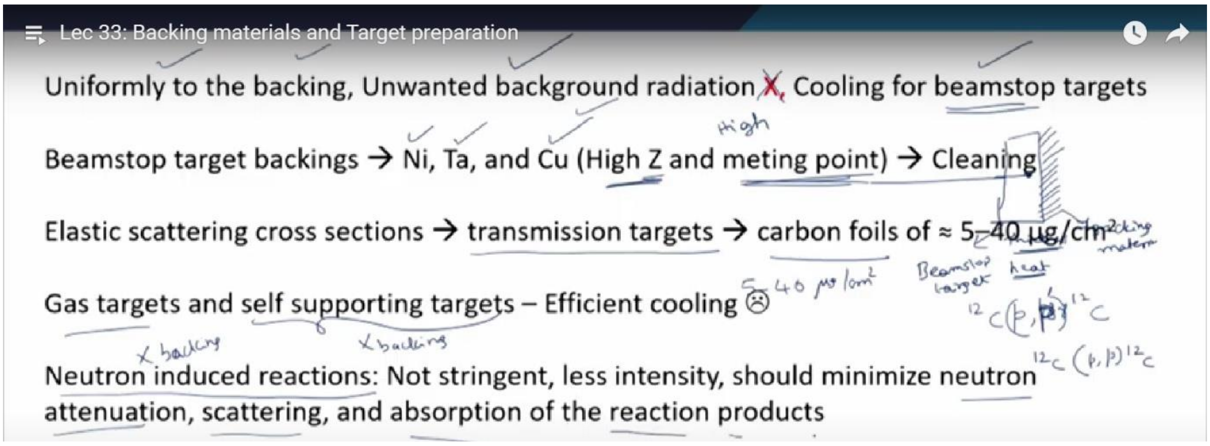
So, it is the observable it is basic yield is the observable quantity in any nuclear reaction. So, how it is connected to the ongoing lecture we are discussing the target materials right. See once you have an idea about the number of gammas emitted the thickness of the backing materials should be such that there should not be more than I mean there should be 90 to 95% of the transmission for the gamma rays emitted in this reactions.

So, because I have discussed about the radiative capture reactions which emits in which gamma rays are emitted. So, I thought it makes sense to do simple calculations for the number of gamma is emitted. So, like this for the given data one can calculate incident beam current if gamma number is given or vice versa. So, like that but here as I said interaction of charged particle with matter has to be analyzed in terms of stopping power based on famous Bethe block formula one can do this. Let us continue with the discussion on backing materials.

What are the important considerations for the backing other important considerations one thickness I have discussed that is it should be 0.5 to 2 mm if the reaction is radiative capture some more important considerations are there for the backing materials and they are uniformity when target material is attached to the backing material. So, the backing material should uniformly adhere to the target material.

Otherwise what will happen in case of non uniformity of the adherence of the target material the degradation of the target material can happen in that portion where adherence is weak. And second important consideration which is a quite important in most of the situations unwanted background radiation we are interested in the reaction between projectile and target material we are not at all interested in the reaction between projectile and the backing material.

So, one has to ensure that backing material should not participate in the nuclear reaction with the projectile beam. If it also undergoes the nuclear reaction with projectile beam then the reaction products may overlap with the reaction products of the target material when it reacts with that projectile. So, it is very important to ensure that target I mean backing material should not contribute to the background.



Another is cooling for beam stop targets see I have said there are two types of targets one is transmission and there is beam stop target. In beam stop target what is happening this is the particle beam and if you beam stop target. So, basically I am saying it is a thickness is very high such that beam gets stopped in this right when beam is stopped within the target material there is a huge chance that lot of heat is produced lot of heat gets produced and it can undergo degradation it can burn.

So, the backing material for this kind of beam stop targets should be cooled. So, that it can extract the heat generated within the beam stop target materials using liquid nitrogen and other means researchers cools the backing materials it is not very easy one has to do lot of simulations for the heat generated and for how long it can withstand the heat generated and how to extract the heat.

So, a different setup has to be arranged. So, these three are the important considerations for the backing materials it has to be uniformity, uniformly adherence to the target material and it should not participate in the nuclear reactions. So, unwanted background radiation is not preferable ok and cooling facility should be there. When target material is beam stop kind of. Now the next question is what kind of beam stop I mean what kind of backing materials are preferred in general and why they are preferred.

So, while discussing the backing materials I have discussed that its thickness should be like this and these are the important considerations. But what kind of materials are preferred and why they are preferred are they satisfying the considerations that I have said. So, normally we use nickel or tantalum or copper because of the high atomic number and a high melting point.

Why high atomic number is helping us as a backing material. See in the nuclear astrophysics in general we deal with the low energies of the projectiles right. And this low energy projectiles if at all they interact with the backing material we have to reduce the probability of reaction to happen and it is well known that for low energy projectiles when they interact with the high z material the nuclear reaction to happen is almost zero.

So, that is the reason people prefer z material like tantalum, copper and nickel. Second consideration as I have said cooling facility melting point is very high the backing material should possess high melting point. So, that the heat generated within the target material in general which happens with the beam stop target materials it should not allow the backing material to get burned.

So, it is important that backing material should have high melting point and tantalum, carbon and nickel they have high melting point. Next I have said many types of nuclear reactions happens within the stars but mostly radiative capture reactions. But many times to understand the synthesis of elements and the nuclear structure in terms of resonance researchers prefer to carry out scattering based nuclear reactions.

It could be elastic scattering and inelastic scattering do you remember one material one nuclear reaction that is a proton on carbon and sometimes if I take the scattering then p p prime 12C. So, proton by interacting with the carbon 12 it undergoes scattering. So, meanwhile it excites the ground state carbon 12 to excited state and during deexcitation gammas are emitted. So, this can always written as p, p prime gamma this is inelastic scattering.

Sometimes it is also I mean useful to carry out elastic scattering experiment like p, p 12C. So, to study the structure of the nucleus which is important for the nuclear astrophysics experiments we do carry out elastic scattering experiments now under this particular situation. So, I am taking different scenarios though mostly I am highlighting the capture reactions. So, in case of elastic scattering reactions when we want to measure the cross sections then which kind of targets are preferred do you have to go for beam stop or do we have to go for transmission targets.

So, the transmission targets are preferred when elastic scattering cross sections are planned because if transmission targets are not used if you go for the beam stop then the probability for getting more counts of the elastically scattered particles will be less. So, we will go for the transmission targets and whenever we use the transmission targets the backing materials that we normally prefer is carbon foils whose thickness.

So, for convenience I am writing here 5 to 40 micrograms per centimeter square you can always divide with the density of the carbon and you can get in terms of centimeter. So, normally thickness can be expressed in terms of mass per area sometimes you can express in terms of energy like in the one of the examples I have discussed it is the keV that is energy loss of the projectile in the thick target.

So, there are various means by which thickness of the target material is or backing material is defined and there is some scenario where backing material is not required. So, we are moving from the requirement of backing materials to non requirement normally when the target material is of gas in nature then there is no need of any backing material. So, important considerations will be humidity and the pressure of the gas.

So, pressure of the gas has to be maintained in such a way that the production of the reaction the reaction products their passage within the gas has to be in such a way that pressure should allow them to get collected at the detectors. So, gas target does not require backing materials sometimes self supporting targets also does not require backing but there is a problem in using the self-supporting target.

Of course it we can use but we have to remember that if the projectile beam is of high intensity then then there is a danger of degradation of the target material and the heat produced within the target material can make it degrade I mean very low quality and sometimes it can evaporate. So, the there is a problem of efficient cooling when self-supporting target is used.

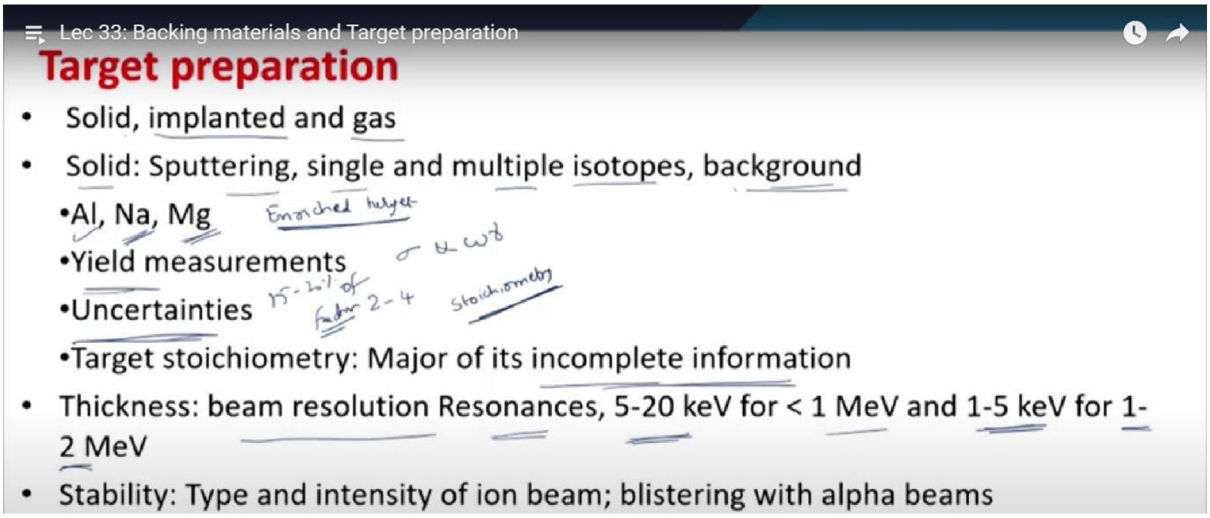
Continuing the discussion after this charged particle induced reactions now the time to see some of the points related to neutron induced reactions. Charged particle reactions plays main role for the synthesis of elements before iron and after iron it is the neutron induced reactions. What are the considerations for the backings and the target materials? If we take into consideration neutron induced reactions fortunately because of the high penetration power of the neutrons conditions are not that much stringent.

Because of the high penetration power the neutrons and not having a charge this makes less stringent when we discuss the neutron induced reactions. But there are few other considerations the backing material or target material should be chosen in such a way that the attenuation of neutrons should be taken care of and the scattering aspect also should be taken care of and absorption of the reaction products also should be taken care of.

If the reaction products are absorbed within the target material or backing material then how can we measure the observables. So, it is important to choose target material and backing metals in such a way that which one should minimize the scattering one should minimize the attenuation and one should minimize the absorption of the reaction products. So, let me complete today's lecture by taking a few points on target preparation.

By the way coming back to the backing materials when we evaporate or when we prepare the target material onto the backing material before that it has to be cleaned thoroughly for removing any surface contamination. So, using several acids followed by the resistive heating beyond 1200 degree backing the materials are generally cleaned. So, that no surface contamination occurs while target is placed on the backing material using appropriate experimental method. Now coming to the preparation of target materials we have crossed the backing materials.

So, it can be like a solid target sometimes it can be implanted targets sometimes it could be gas targets. And I cannot cover the preparation methods of all these types of target materials in



general solid targets are prepared mostly using physical evaporation method or sputtering method. And sometimes it can have a single element or sometimes it can have more than one isotope there. There is a problem of overlap of the reaction products and background also should be very less such that in such a way that target material should be prepared.

For example here I am taking aluminum it is very simple take aluminum 27 foil you heat it and using some appropriate backing material you deposit the aluminum target material. So, there is no issue at all but if I want to have reaction with sodium 23 say then we have to go for compounds and evaporation of compounds is a big challenging thing. And then another challenging part is magnesium if you want 24 25 26 isotopes of magnesium if you take natural magnesium have it has all these isotopes and projectile can initiate with all these isotopes.

So, how to avoid this very simple go for isotopically enriched target material enriched target materials. Of course it would be costly there is no doubt and at the end of the day what we normally measure it is the yield of the reaction and from that we measure the cross section and also strength of the resonances. Of course if it is the nuclear reaction is a resonant type all right.

And uncertainties is one of the important parameter same reaction different research groups they report the cross sections and many times they are different by a factor of 2 to 4. So, the difference of the cross the difference in the cross section values differ reported by different research groups they are mainly due to people attribute to the stoichiometry of the target composition. So, stoichiometry of the target is one of the major challenges in reproducing the cross section value of a nuclear reaction.

So, there is an incomplete information regarding the stoichiometry. So, complete information of the target stoichiometry is not possible to get. So, that leads to the uncertainty many times you will see uncertainty of the order of 15 to 20% also. And regard how thick how thick it should be? Of course it depends on whether it is resonant reaction or non resonant reaction and beam resolution it depends if it is resonant reaction the resonance what is the separation it is there.

Less than that the beam resolution should not be there for example if the beam energy is less than 1 MeV then beam resolution should be of the order of 5 to 20 keV and for above 1 MeV up to 2 MeV with the beam the thickness of the target material should be of the order of 1 to 5 keV all right. And it should be very stable the stability of the target material of course depends on the type of the beam and also the intensity of the beam.

When I say type if I go for alpha beam then there is a problem for the blistering and the implanting of the alpha particle in the target material can lead to that lattice defects. So, all these things should be taken care of. So, in today's lecture I have discussed number of gamma rays emitted in proton-induced reaction with carbon and then some of the important considerations with the backing materials.

And then target materials when we discuss what are the important considerations both the charged particle induced and neutron induced reactions. So, in the next lecture we will discuss detectors which is a one of the most important aspects of the experimental nuclear astro physics, thank you very much.