Nuclear Astrophysics

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Lecture - 37

Activity Method

Yes, students welcome to today's lecture on experimental techniques in nuclear astrophysics. So, as part of experimental aspects of nuclear astrophysics I have been discussing target materials, backing materials, target chambers and then nuclear radiation detectors in which I have discussed ionization chambers, scintillation detectors in detail and semiconductor detectors. To summarize that aspect.

Ionization chambers and sodium iodide detectors and high purity germanium detectors they are widely used in nuclear astrophysics. Ionization chambers they have unique advantage of making them in large size it is really versatile. What is the advantage of having large size? Not only the detection of high energy because here the high energy does not matter in the case of ionization symbols which are meant for the charged particles.

The absorption of charged particles is always taking place because the range is not very high being you know a charge associated with it. But having large size ionization chambers improves the probability of accepting more particles. So, more solid angle more acceptance of the particles from the source. So, this is one of the unique features of ionization chambers. And one can get the precision position information also by using more than one anode wire which we call as multi-wire gas detector.

So, instead of one wire you use multiple wires so, what will happen? The location of ionization can be determined by taking the signals from different wires so this multi wire proportional counter helps in getting the location of interaction. So, one cathode but multiple anodes can be used in the ionization chambers. Ionization detectors having gas as active volume and 100% collection efficiency for the charged particles. Like ionization chambers, semiconductor detectors also have 100% collection efficiency detection efficiency for charged particles.

So, we are dividing into charged particles and non-charged particles like gamma and neutron. So, for charged particles highly preferred detectors are ionization chambers and semiconductor detectors which have 100% detection efficiency. And the problems associated with ionization chambers can be handled by going for semiconductor detectors because of less value of W that is energy required to produce one pair of charge carriers like electrons hole pair. Less value of Fano factor it is very much possible to get excellent energy resolution. Yes, we have to compromise with the acceptance angle because semiconductor detectors cannot be grown in very large size. And one of the major problems with semiconductor

detectors is the chances of undergoing damage because of the neutrons. They are insensitive to neutrons there is no doubt but they will undergo damage because of the neutrons.

Coming to the gamma rays, highly preferred detectors are scintillation detectors because of their very good detection efficiency due to their high density and excellent light yield. And widely used scintillation detectors are sodium iodide detectors and nowadays many other scintillation detectors are comes into picture. But still sodium iodide is ruling the scintillation detector world and regarding new scintillation detectors lanthanum bromide and lanthanum halides.

They suffer from internal reductivity but if we can handle them, it is very good in terms of resolution and efficiency. And if you want detect the gamma rays with excellent energy resolution by compromising little bit with the efficiency. Then one can go for the high purity germanium detectors in terms of energy resolution no detector can beat high purity germanium detectors.

And why high-quality germanium detectors have external energy resolution as I said there are less value of W and less value of Fano factor and efficiency collection of the charge carriers. But the major issue is that one has to cool using the liquid nitrogen so that thermal fluctuation cannot interfere with the original data that we are looking for. So, this was about the detector world that we discussed till the previous lectures where we will use all these detectors to measure the yield of the nuclear reaction.

So, what do you mean by measuring the yield of the nuclear reactions? Number of nuclear reactions happened which leads to the emission of particles in it could be protons, neutrons or alpha particles. By measuring them we measure the yield of the nuclear reactions already have discussed in the previous lectures. What is the meaning of yield of the nuclear reaction? Which is very important to measure the nuclear cross section.

Once you have the cross section in hand we can go for the measurement of strength of the resonance in case of resonant reactions. And one can go for the reaction rate calculation. So, the aim is in how many ways one can measure the nuclear reaction cross section. In today's lecture I will discuss a method which is quite interesting and easy of course it has its own limitations. So, I will discuss the advantages and also the limitations of this method and the method which I am going to discuss in today's lecture is activity method which is also called as activation technique.

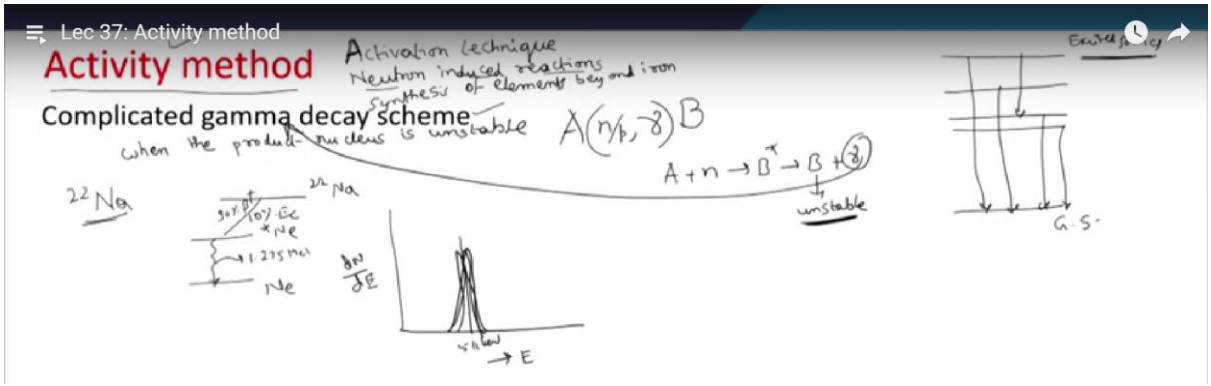
Mainly it is used for neutron induced reaction and I am sure you remember the importance of neutron-induced reactions mainly for synthesis of elements beyond iron. So, you can understand the importance of neutron induced reactions and in order to measure the cross sections of these neutron induced reactions this activation technique is quite useful when this activation technique comes into picture.

See when projectile reacts with the target nucleus whatever compound nucleus is formed. Assuming the reaction is through the formation of compound nucleus which is the common case the compound nucleus decays to the ground state by emitting various particles. Assume

this compound nucleus is emitting gamma rays during its journey to the ground state. Let me draw like this so, this is a compound nucleus and this is a ground nucleus.

Depending on the existence of the energy levels one can expect lot of transitions as per the selection rules. So, this is the ground state and this is the excited states. How do you measure the cross section for this kind of reaction? You need to measure all the gamma rays in this reaction. The gammas which are emitted in this reaction. You need to measure all of them and whenever you face a complicated gamma ray decay scheme when large number of gamma is involved.

It demands larger number of detectors for efficient measurement. And if you have less, number of detectors, you need to place at different locations many a times and you have to acquire large amount of data. So, there are issues when the compound nucleus gives rise to large number of gamma rays during its journey to the ground state from excited state. So, when complicated gamma scheme you come across. Or when you do not want to have beam induced background. Then this activation method really helps us. So, how it is operated what is the derivation of formula to find out the number of nuclei which is a yield of the nuclear reaction which gives information about the nuclear reaction cross section that I will discuss in today's lecture.



So, when we have a complicated decay scheme the activation method is very much important, I mean it is very useful. So, in this complicated gamma decay scheme when you want to get rid of it the activation method is useful only when the product nucleus is unstable. For example, target nucleus A and n or you can take P and if it is capture reaction mostly it is the capture reaction which plays important role in the synthesis of elements.

Then the energy productions within the stars and you have the product nucleus B. So, when a + n gives rise to B in the excited state you are getting B + gamma and I am saying this gamma as complicated decay scheme. Sometimes if this B is unstable so the transition is taking place from the excited state to ground state but this ground state product nucleus is itself unstable. And if the half-life is more than a few seconds then one can prefer this activation method.

So, what is the technique? What is the principle in this activation technique before that let me take some gap and explain you the measurement using a radioactive nucleus which decays through positron. So, if you remember one of the widely used gamma source sodium 22 it

decays to the excited state of neon which further de-excites to the ground state of the neon and this gives rise to 1.275 MeV gamma.

Here 90% positron and 10% electron capture. So, this is a positron emitter, I have told you in one of the previous classes how to differentiate a source which is emitting beta minus from a source which is emitting beta plus. So, this is sodium 22 apart from the emission of 1.275 MeV gamma ray because it is undergoing decay through positron. This positron will interact with one of the electrons in the surrounding environment gives rise to the emission of 511 keV gamma is in opposite direction.

So, when you see the energy spectrum dN by dE versus E so you will get a peak around 511 keV, it is basically I am drawing like this a peak around 511 keV. Now this detection of 511 KeV gamma rays from a positron emitter is the basic principle in the activation technique. So, now let me discuss the mathematical aspect of this activation technique.

Let me start with an example alpha induced reaction with nitrogen 14 which gives rise to a compound nucleus in the excited state, say fluorine 18 and during de-excitation it emits gamma rays. So, we are not measuring these gamma rays fluorine 18 from the excite state to ground state whatever number of gamma rays they are emitted, we are not discussing these gamma rays. In fact, this fluorine 18 is unstable and whose half-life is 110 minutes.

So, it is unstable and it decays via positron with a half-life of 110 minutes. So, the activation method involves two steps number, one do not place any detectors within the particle accelerator, just allow the projectile to react with the target nuclei. So, allow the irradiation of target by projectile and measure, then in the second step you remove the target material take to the next room or in another laboratory where detector is placed.

You can use a high purity germanium or scintillation detector and you measure the 511 KeV gamma rays and you measure the residual activity. The measurement of residual activity gives information about the yield of the nuclear reaction because when I say measurement of residual activity, what does it mean? I am measuring the number of fluorine 18 nuclei produced and number of fluorine 18 nuclei produced means number of nuclear reactions happened.

That gives us information about the nuclear reaction cross section. Instead of measuring the gamma rays emitted from the compound nucleus or in this case a fluorine 18 only from a excited to de-excited state. I am not measuring those gamma rays simply I am irradiating the target with the projectile no detectors at all in the first step. And I will stop the beam whatever target has been irradiated with the projectile which I am saying is activated.

That is why we are saying this method as activation method. Take this activated target material into another room keep in front of the detector because this activated material is emitting 511 keV gamma rays continuously. You catch these 511 keV gamma rays. From that you measure the number of fluorine 18 nuclei and this information of the fluorine 18 nuclei number gives us the yield and then it we can calculate the cross section.

So, what are the steps involved mathematically that let me discuss. So, when I want to measure the residual activity the rate of say I am considering this as x and say p or n gamma ray and Y, Y is the residual nucleus. So, what is the rate of increase of residual nuclei dN y by dt = production rate P as a function of t - the rate with which decay is happening by a gamma emission. So, this is production rate and this is decay rate, so the rate of production and the rate of destruction.

The rate of production - the rate of destruction that means rate of decay gives us the time evaluation of the residual nuclei and how to represent this production rate which is equal to the cross section of the nuclear reaction. Of course, it is a function of space and the energy and the number of target nuclei X denotes the number of target nuclei and the flux of the incident beam. Number of projectiles per unit area per unit time is flux.

And X denotes the number of target nuclei and sigma denotes the cross section. The product of these three quantities gives us information about the production rate. And decay anyway it is happening and it is very simple to understand because the moment because of the irradiation target nuclei get activated and produce a residual nuclei. They are immediately decaying as per the half-life, so you need to consider both of them.

So, solve this differential equation and you will get the solution in terms of residual nuclei Ny. So, solving this differential equation you will get Ny as a function of t gives sigma X phi divided by lambda gamma 1 - e to the power of - lambda t. So, what is this Ny? As I said it is a time evolution of residual nuclei.

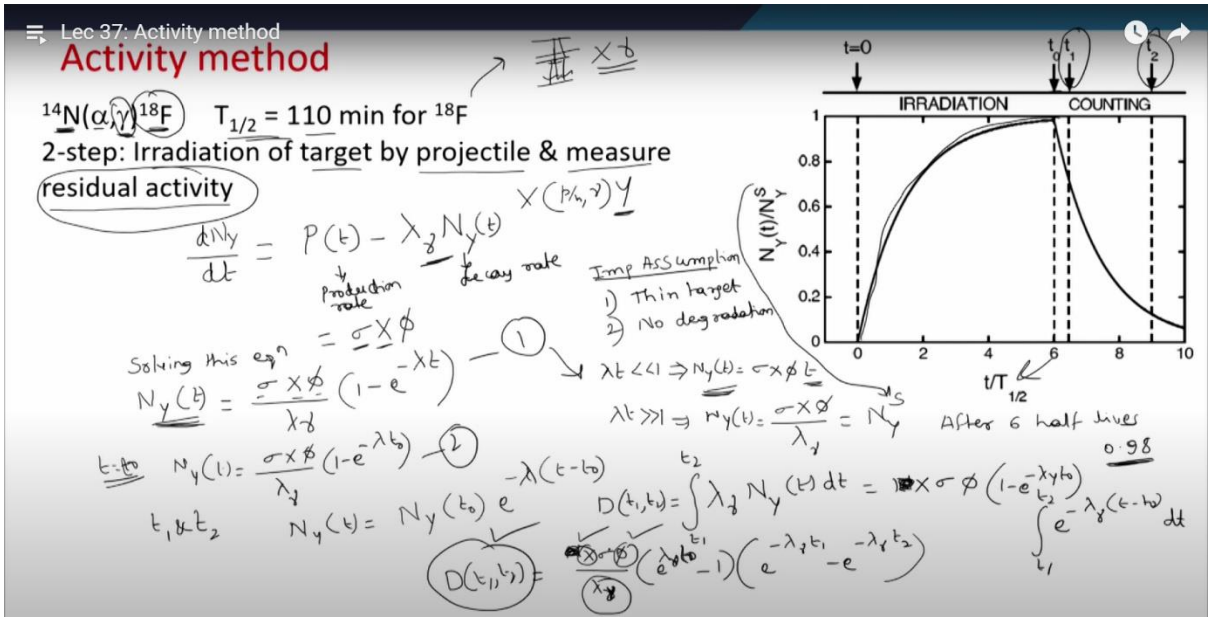
When I said this sigma X phi the target thickness is considered such that the energy loss is not very high. It is constant throughout its journey in the target material. Now you can always ask from thin target we can assume that whatever thick target fine one has to integrate this over the thickness. Then one has to integrate over the energy also because the energy loss is different at different locations in terms of the thick target. So, I am assuming that it is a thin target.

Important assumptions number 1, the target is thin enough. So, the energy loss is almost constant. Number 2 no degradation of the target because if there is a deterioration in the target material due to any reason there will be change in the target nuclei and here, I am assuming there is no change in the target nuclei that is X so, these two assumptions are important. So, whatever mathematics I am doing, it is under some important assumptions which are normally applicable in most of the cases by taking proper precautions. Now this is the time evolution of the residual nuclei so what will happen if the time reaches t0 then we can write down Nyt as sigma X phi lambda gamma 1- lambda t 0 but here in this particular case equation number 1 if I say this equation 2 for equation 1, I want to discuss 2 different scenarios.

If lambda t is much less than 1 then this n by t can be written as sigma X phi into t you can solve yourself it is very easy so with time N y is increasing linearly so in this diagram you can see. So, here it is increasing linear after up to certain time. Now if it is much greater than one then N y t is given as sigma X phi divided by lambda and this is also called as N y s now this is the same N y s I am using here.

So, after about 6 half-lives you can see after about 6, half-life and the x-axis it is basically time divided by half-life and if t by t1/2 is about 6 then the number is about 0.98 so almost it has reached saturation. So, after t = t0 I have switched off the particle accelerator beam. I have entered into the particle accelerator beam and removed the target and went into another room are other than that irradiation region and kept in front of a detector.

This irradiated activated material is emitting 511 keV gamma rays continuously why because it is a positron emitter. So, by now it must be clear to you this technique is valid only when the residual nucleus is decaying through positron otherwise it is not possible. Now you got rid of all beam induced background and there is no need of measurement of all gamma energies which is happening before the residual nucleus is reaching to the ground state.



Now after irritation is stopped and kept in front of the detector now you have measured the gamma rays in between two timings like t 1 and t 2. So, how you can write down this equation for the number of nuclei this N y t is and now I am writing after t = t 0 the number of residual nuclei is undergoing a new decay so P of t is 0. When P of t is 0 only decay is happening how this time evaluation of residual nuclei is happening very simple.

N y t is nothing but N y into t 0 e to the power of - lambda t - t 0. So, this is how decay is happening. Now if I want to measure the number of particles within two time slots like in this diagram if you see t 1 and t 2 you see there is a small gap between t 0 and t 1 so after irradiation is stopped, I will wait for some time. So, let decay start and I will start at t 1 and I will close at t 2. In these two time slots I will measure the number of particles.

How to represent it mathematically? It is nothing but the integral of activity lambda y N y from t 1 to t 2 lambda that is decay is happening. And N y this t and dt and the number of disintegrations in this period that means t 1 t 2 is given by this so, this is nothing but N x sigma

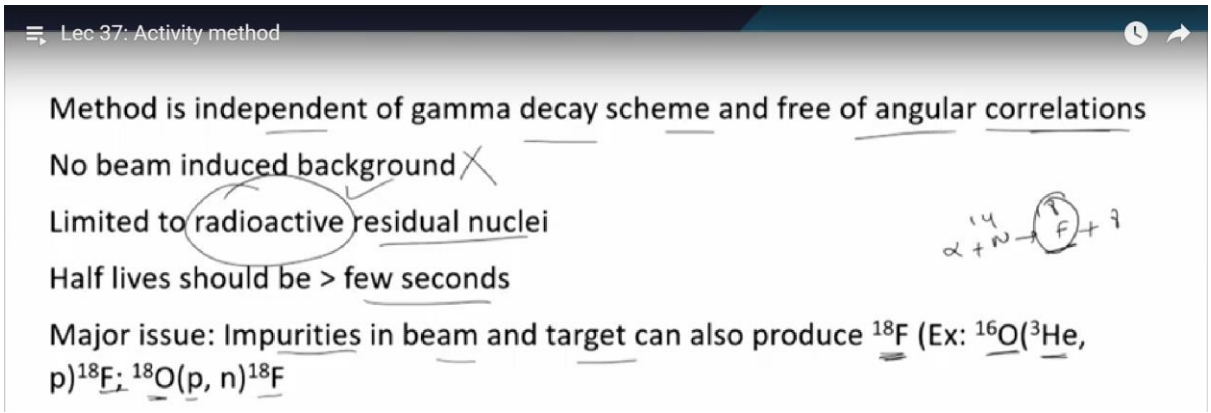
phi 1 - e to the power of - lambda y t 0 t 1 to t 2 e to the power of - lambda gamma t - t 0 dt. So, solving this you can easily get N x or simply you can write down.

So, this is basically X sigma flux divided by lambda y e to the power of this lambda gamma lambda y t 0 - 1 e to the power of - lambda gamma t 1 - e to the power of - lambda gamma t 2. So, here I have given you the number of disintegrations between t 1 and t 2 how it is going to help us. See the equation carefully. By measuring the number of disintegrations between t 1 and t 2 on the left hand side I am measuring this D between t 1 and t 2.

So, experimentally I am measuring these target nuclei I can always get the information flux I can get from the particle beam and decay constant of the nucleus I am aware of it, t 0, t 1 and t 2 that we are setting. So, like this one can measure the cross section. So, the cross section of this nuclear reaction of alpha + N 14 can be measured not only by measuring the gamma rays emitted from the excited state of the fluorine but also from the decay of the residual nucleus that is fluorine 18.

So, by detecting the number of gamma rays between t 1 and t 2 using this mathematical equation one can always find out the cross section of the nuclear reaction. So, this activation technique has a major problem.

Like if we see I mean let me repeat the advantages. So, it is independent of the gamma decay scheme and it is free of angular correlations. So, no need to use a lot of detectors and there is no beam induced background. And it is of course limited to the case when residual nucleus is radioactive. If it is not radioactive there is no point in using the activation technique and of course half-life should be greater than few seconds.



One of the major issues is impurities in the beam or the target because same fluorine 18 earlier if you remember the reaction error it was alpha nitrogen 14 alpha + nitrogen 14 is giving rise to fluorine 18 + gamma. This fluorine 18 is unstable. We are measuring the gamma ray decaying through fluorine 18 by positron decay. But this fluorine 18 also can be formed because of the contaminants like oxygen 16 + helium 3 and proton and oxygen 18.

So, these contaminants can be present within the target material and the beam and the same residual nucleus is forming. And how to differentiate is extremely difficult so one has to be careful while using the activation method what are the contaminants which can hamper our nuclear reaction.

So, to summarize today's lecture. I have discussed one important experimental technique to measure the nuclear cross reaction cross section.

Provided the residual the product nucleus is radioactive in nature and which decays via positron. In the next lecture I will discuss some more mathematical aspects of the experimental techniques. Thank you so much.