Nuclear Astrophysics

Prof. Anil Kumar Gourishetty

Department of Physics

Indian Institute of Technology – Roorkee

Lecture – 34

Contaminants and Radiation Sources

Welcome to today's lecture in which we are going to see the role of contaminants. How they will affect the experimental aspects of nuclear astrophysics even nuclear reactions in general as well. So, which are applicable even for the experiments or nuclear reactions relevant for astrophysics. In the previous class I have discussed the considerations when backing materials are used and target materials are used and as part of the continuation of target materials and associated equipment.

So, let us see one more parameter that is contaminants and after discussing the contaminants I will throw some light on nuclear radiation detectors.

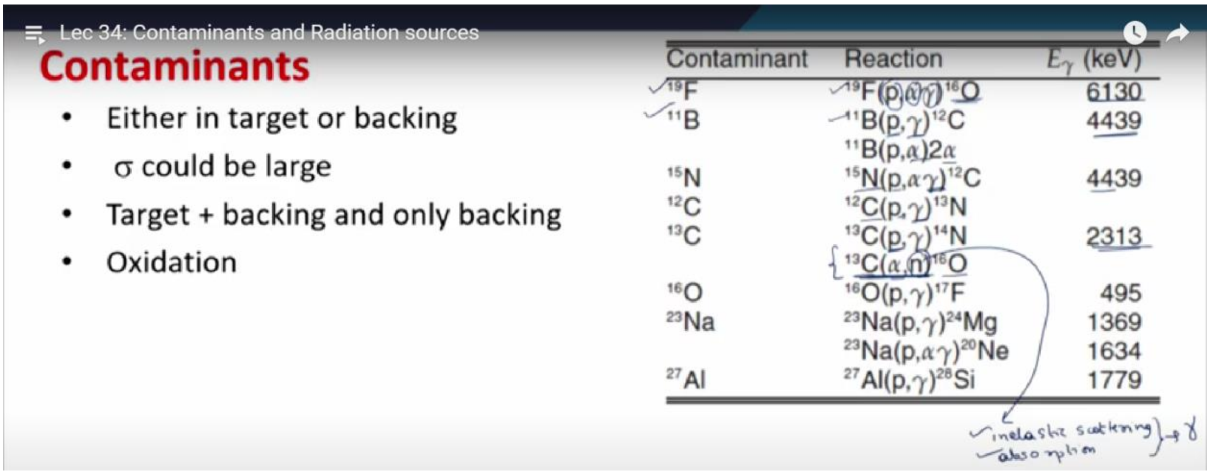
What are the general aspects of the detectors and how many types of detectors are available and relevant for nuclear astrophysics related experiments. And how the spectroscopy of charged particles, neutrons and gamma rays can be studied using various types of nuclear radiation detectors. So, let me see how much I can cover in this lecture about the detectors remaining part I will continue in the next lecture.

So, coming back to the target and associated equipment it's contaminants. Many times the presence of contaminants either in target material or in backing material that means the support for the target material in the back side not the supporting material for holding the target material. So, in the backing material or in the target material the presence of contaminants can hamper the studies of nuclear reactions.

You can always say how the contaminants can disturb the data that we are looking for because the concentration is very small in this backing materials and target materials. Yes, the concentrations of these contaminants are very small there is no doubt however depending on the incident beam type and energy there is always a great possibility that the cross section of these contaminants with the incident beam could be very high. The probability for the reaction to happen between the incident beam and the contaminants could be very high.

So, because of the high cross section the emission of particles may be gamma rays maybe alpha particles or some scattered particles or neutrons they will always contribute to the original data that we try to collect from the detectors. So, we should ensure that contaminants are not hampering the nuclear reactions of our interest. Then how to eliminate the contribution of contaminants?

First you would run the experiment by taking the target material and the backing material you see whatever count rate is there from the detectors because it is the counts or count rate which helps us in getting the information of a yield of the nuclear reaction and that yield is used to find out the cross section and then reaction rate, S factor and what not. So, take the data by considering first target and backing combination.



Lec 34: Contaminants and Radiation sources

Contaminants

- Either in target or backing
- σ could be large
- Target + backing and only backing
- Oxidation

Contaminant	Reaction	E_γ (keV)
✓ ^{19}F	^{19}F(p,αγ)^{16}O	6130
✓ ^{11}B	^{11}B(p,γ)^{12}C	4439
	^{11}B(p,α)2α	
^{15}N	^{15}N(p,αγ)^{12}C	4439
^{12}C	^{12}C(p,γ)^{13}N	
^{13}C	^{13}C(p,γ)^{14}N	2313
	^{13}C(α,n)^{16}O	
^{16}O	^{16}O(p,γ)^{17}F	495
^{23}Na	^{23}Na(p,γ)^{24}Mg	1369
	^{23}Na(p,αγ)^{20}Ne	1634
^{27}Al	^{27}Al(p,γ)^{28}Si	1779

✓ inelastic scattering
✓ absorption
} → γ

And then you remove the target material take the reaction only with the backing material and you take the difference that will help us in getting rid of the contribution of contaminants present in the backing material all right. So, this is how one can take one can take care of the contribution of contaminants in the backing material.

So, there are some other issues as well for example oxidation especially when neutron induced reactions are considered metal samples are been used then oxidation is one of the problems and sometimes it can change the composition of the target material. And because of the hygroscopic nature that means absorption of the moisture from the air the target material can develop change in the composition.

And because of the change in the composition what will happen of course there is a change in the data that we are looking for. What are the famous or important contaminants in nuclear reactions. Let me show you a table. So, here is the table one of the common contaminant is fluorine 19 and you know proton induced reactions they are very important for nuclear astrophysics. When they interact with F19 you will get alpha and gamma rays and oxygen 16 as the product nucleus which is stable.

You see the energy of the gamma ray about 6.1 MeV the target material if causes a nuclear reaction in which the gamma rays of energy said 6 to 6.5 and then in that case this fluorine 19 also is giving rise to 6.1 MeV gamma ray. So, there is an overlap. So, you can see the emission of gamma rays of energy of 6.1 MeV can change the count rate if the nuclear reaction of our interest also emits gamma rays of energy around this 6.1 MeV.

So, how to take care of this there are methods to take care of the contribution of contaminants the second contaminant boron 11 when proton reacts with boron 11 you are getting gamma ray here the energy is 4.4 MeV and it can also emit alpha particles of different energies and proton with nitrogen 14 can give rise gamma ray of energy 4.4 protons sometimes by reacting with carbon 12 it can give you gamma rays same like 4.4 MeV.

And then carbon 13 this is one of the important contaminants which can hamper the nuclear reaction of our interest here 2.3 MeV gamma is emitted. Now this is a one of the major contaminant C13 which is giving rise to reaction of alpha, alpha plus carbon13 gives rise to oxygen 16 plus neutron and these neutrons carbon 13 when it reacts with alpha that means incident beam we are assuming is alpha.

The reaction can lead to the emission of neutrons and these neutrons poses problems when detector background is taken. So, these neutrons will certainly hamper the detector background second way these neutrons by undergoing inelastic scattering with the surrounding material or absorption anything can give rise to gamma ray and this gamma rays can hamper the detector count rate.

So, we do not want this gamma rays from carbon 13 which is giving rise to neutrons and those neutrons by interacting with the surrounding materials they are via absorption or inelastic scattering they are giving the gamma rays to the detector and it is polluting the data which we are expecting from the nuclear reaction of our interest. So, this is one of the important reaction in which contaminant can hamper the nuclear reaction. So, some more reactions are given here and corresponding gamma energies all right.

So, after discussion on contaminants before that I have discussed target materials backing materials. Now it is a time to discuss the second important aspect of experimental nuclear astrophysics and it is nuclear radiation detectors. So, detector as name suggests it detects and measures the nuclear radiation, how it works? How many types of detectors are available and what kinds of detectors are preferred for the nuclear reactions relevant for the astrophysics.

You might have seen GM counters, scintillation detectors in your teaching laboratory of course the knowledge that you might have gained by doing experiments with GM counters and scintillation detectors will surely help you in understanding the detectors aspect that I am going to discuss. So, before the discussion on detector I can take up I would like to spend some time on the radioactive sources and interaction of radiation with matter.

Because before using the detectors for the nuclear reactions relevant for astrophysics you need to test the detectors in the laboratory. You need to test and calibrate the nuclear radiation detector before using it for the nuclear reaction inside a particle accelerator when particle beam falls on the target material because of the nuclear reactions when particles are emitted detector is going to detect them.

If they are charged particle then one can always place the detectors inside the target chamber because the travelling of other particles from the target material the location where the nuclear reaction is taking place before reaching the detector if the distance is large they will get absorbed. So, generally the detectors for detecting the charged particles like Hoyle state measurement.

If we want to detect the alpha particles when reaction takes place for the study of Hoyle state then alpha particles are emitted immediately after the target materials are target material and near to the target material you need to place the charged particle detector and that whole environment has to be within the vacuum region that is why we try to maintain about 10 to the power of 6 to the power -6 torr or if possible if you have a better vacuum system you can go for 10 to the power of -8 -9 torr also.

So, that the loss of charged particles is very less all right. So, as I said detectors have to be calibrated using radioactive sources in the laboratory not particular accelerator beam hall but in the laboratory you have to test the nuclear radiation detectors whether it is performing well or not. To test the detectors of course one needs radioactive sources. So, what are the widely used radioactive sources to test the nuclear radiation detectors. Let us discuss one after the other.

Let me start with most widely used gamma source across the world Caesium 137 it is a mono energetic gamma source. So, I will explain the decay scheme in detail of one or two sources remaining sources I expect you to study yourself through textbooks or material available in the internet. So, let me spend enough time on the decay scheme of a radioactive source in this case caesium 137 which is widely used to calibrate and test the nuclear radiation detector.

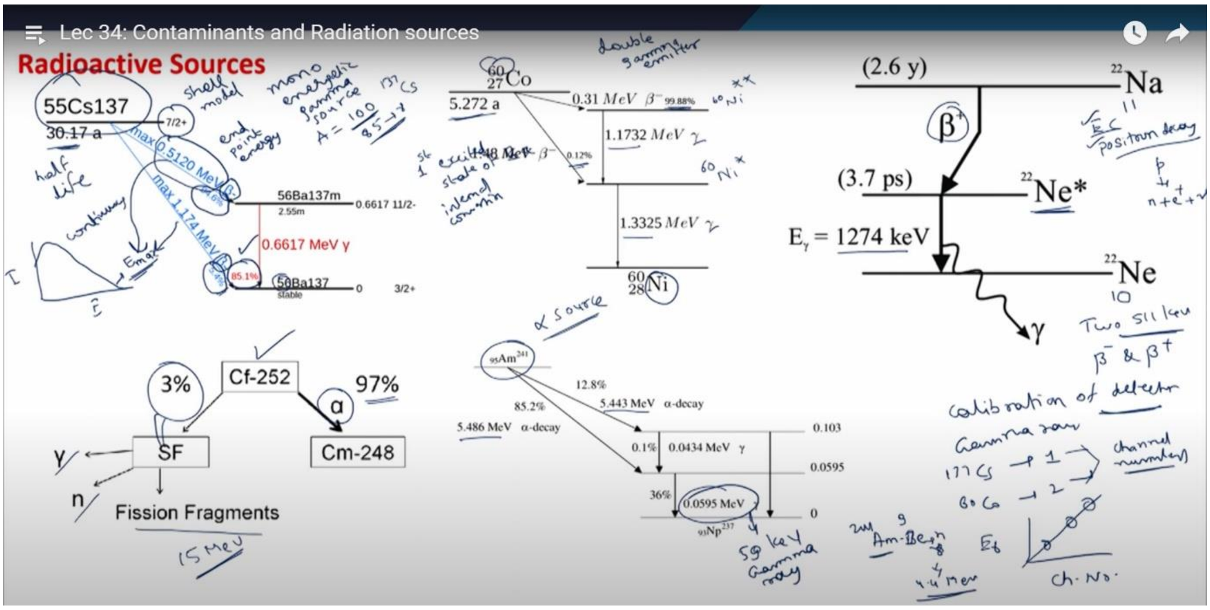
Of course this is the case when the nuclear reaction emits gamma rays and by detecting the gamma rays we want to measure the cross section of the nuclear reaction. See here so, it is 30.17 years half life all right and the spin and parity is given by 7/2 plus you know how to get this using the shell model that I am not discussing here. So, because it is unstable it will decay by beta minus because neutron number is more and 94.6% decays to the first excited state of barium.

You can see barium 56 the atomic number has increased by 1. So, 94.6% of the caesium nuclei decays to first exit state of the barium and remaining 5.4% will decay directly to the ground state of the barium in any case it is a beta minus whenever you see the decay scheme of any radioactive source especially if it is beta minus. Then some energy value is always given in the decay scheme and in this case 0.512 MeV is the end point energy of the beta rays.

Because you know if you see the energy versus the intensity of beta rays it basically is like it is a continuous distribution is not it, it is a continuous distribution and this is the end point energy E max. And here the 0.512 is the maximum energy of the beta particle in this decay similarly in this 5.4% 1.174 is the maximum energy of the beta minus particle. So, if at all you can measure the energies of the beta particles using some method.

Then it is not only one energy because the energy distribution is continuous in case of beta sources right now in 94.6% only 90% of it will decay to through the gamma rays remaining goes to the internal conversion all right. So, 90% of 94.6 gives to gives rise to 85.1%. So, if you have 100 Caesium nuclei how to get it the manufacturer in general gives the activity normally in terms of micro curie or becquerel and you know how to convert micro curie to becquerel. So, if 100 Caesium -137 nuclei undergoes decay 85 gamma rays are emitted from the source in all directions if it is point isotropic source.

So, in general point radioactive sources are used in general sometimes we can always use Marinelli beaker and extended sources kind of thing. So, I am using the simplistic version that is point radioactive source which emits gamma rays in all directions. So, this is a decay scheme of Caesium 137. Second cobalt 60 it is a double gamma emitter. When I say this what does it mean its half life is 5.27 years and cobalt 60 mass number because of the neutron rich one neutron gets converted into proton.



And 99.88% will reach to the second exited state of the nickel and as part of the selection rules it goes to the ground state via emission of 1.173 and 1.332 MeV gamma rays and very small percent like 0.12% will decay to the first exit state of nickel, nickel 60 first exited state and nickel 60 second exited state. So, one nucleus is giving two gamma rays of two different energies.

So, this is one of the source which can help us to test the ability of detector in terms of resolution that I will discuss in the course. Now let me show you a source which emits which decays through beta plus positron emitter. So, beta plus you can see sodium 22 atomic number is 11 all right. And when positron reacts with the electron in the surroundings it will give you two 511 keV gamma rays and the reaction happens through both electron capture and also positron decay.

So, you should know the meaning of electron capture, position decay you can go through any nuclear physics textbook it will be explained very clearly all right. So, via electron capture and positron decay when sodium 22 undergoes decay they reach to the first excited state of neon 22 via electron capture via position decay in both manners it reaches to the first excited state of the neon 22 atomic number decreases by one.

Because proton is basically getting converted into neutron plus positron plus neutrino that reaction you know very well. So, we have 1.275 MeV gamma ray in addition to that the beta plus reacts with electron in the surroundings it gives you two 511 keV gamma rays. So, little bit deviation from the discussion let me pose your question. You have been given a source for example this is a radioactive source.

Whether it is a position emitter that means beta plus or beta minus what kind of decay is happening? How to know that? It is quite simple if this radioactive source emits positrons then from the detector you will get a signal corresponding to 511 keV always. So, in the response of the detector if you find 511 keV that means the radioactive source is decaying through beta plus and if there is no 511 keV it means the source is decaying through beta minus.

So, that is how one can differentiate beta minus decay and beta plus decay through radioactive sources. Now after discussing this gamma sources let me show you one of the widely used neutron source in the laboratory. Why do we need neutron source because as I discussed in S process R process the seed nuclei has to absorb the neutron and it gives rise to new element a new isotope new nucleus is formed.

But that neutron is emitted in some reaction if you want to study that nuclear reaction in which neutron is emitted then you need to use neutron detectors in the particle accelerator. So, as I said before putting the detector in the particle accelerator you have to keep in the laboratory and you have to test and you have to calibrate it you have to see its performance. So far that also you require one neutron source in the laboratory.

So, for producing the neutrons though there are nuclear reactions which can emit the neutrons we have a few sources available in the laboratories using which one can test the performance of the detectors for neutrons. And one of the most widely used neutron sources across the world is fission source californium 252. So, this is the californium 252, 97% of californium 252 this is called as transition probability, decays via alpha process.

And remaining 3% decays by a fission process this is called as spontaneous fission. And you know in the spontaneous fission you will get fission fragments you will get gamma rays you will get neutrons. And these neutrons and gamma rays they are not mono energetic they are distributed in terms of energy. So, you measure the neutrons of different energies using detectors which you want to use for nuclear reaction in the particle accelerator. And the energies of the neutron ranges from say around 1 MeV to 15 MeV.

Now after this neutron let me show one widely used alpha source that is americium 241 in the laboratory teaching laboratory in your department or in university or institute if you have Rutherford alpha scattering experiment or alpha spectrometer you can see it could be either plutonium or americium. So, normally the energies ranges from 5 to 7 MeV. Here in case of americium 241 the energies of the alpha particle they are two different numbers you have like it could be 5.486 MeV it could be 5.443 MeV.

Here one interesting point I would like to highlight you see here 59 keV gamma ray. You know gamma rays are highly penetrating their energies are higher than normal characteristic x-rays. So, this gamma is energy less than 100 keV is not very easy to get. So, sometimes if you want to see the response of detectors for low energy gamma rays go for americium 241 it emits 59 keV gamma rays.

So, it is widely used you know for low energy measurement of the detector and anyway alpha rays will get absorbed in the air do not maintain the vacuum between the detector and source. So, you have only gamma ray. So, you can get rid of alpha particles by maintaining some distance between source detector and gamma ray can easily pass through the air and falls on the detector it gives you response for the 59 keV gamma ray.

So, these are the radioactive sources which are widely used for testing the detectors. Now I have used a word calibration of detector. So, let me take for the simple case gamma rays how do you do it? You use 137 caesium and you use the 60 cobalt it gives one energy it gives two energies and these three gamma rays will give some channel numbers in the electronics and you plot channel number on the x axis energy of the gamma on y axis and in general you will get some kind of a linear plot.

So, with this one can check the linearity of the detector you can always ask okay we are calibrating the detector only up to 1.33 MeV correct if the gamma is emitted in the nuclear reaction of our interest the energy range is like 10 maybe 15 maybe 20 MeV then one can go for nuclear reactions for calibrating the detector itself. But here I am discussing the calibration of detectors within the laboratory using radioactive sources.

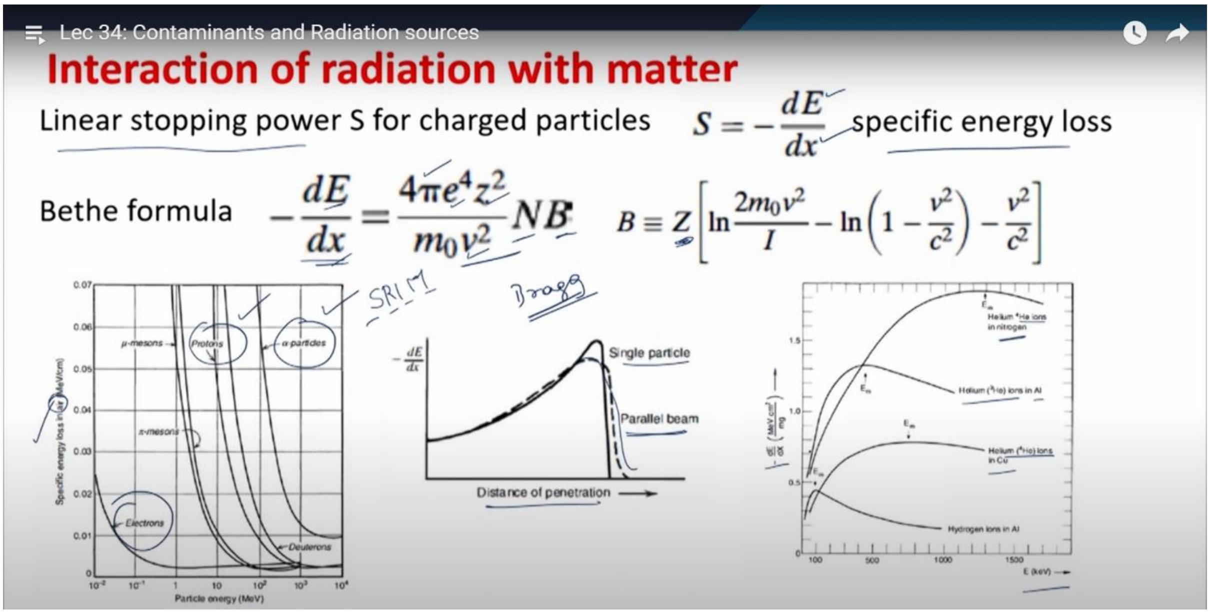
For high energy gamma rays yes there is one source that is a americium-beryllium source americium 241 beryllium 9 source where americium emits alpha reacts with beryllium gives rise to neutrons and also gamma rays. And here the gamma ray energy is 4.4 MeV. So, you will get one mono energetic gamma ray from the americium beryllium. So, after 1.33 MeV by cobalt 60 you have to go for 4.4 MeV in between these two numbers it is difficult to get the radioactive sources which emits gamma is in this range.

So, once you calibrate the detector you place in the particle accelerator beam hall and detect the gamma rays emitted by the nuclear reactions all right. So, let us continue. When the radiation is emitted from alpha source beta source or neutron source or gamma source they are detected and measured with the help of a detector. But how do they interact with matter it could be liquid gas or solid material.

So, it is very important to understand the interaction of nuclear radiation with material accordingly you can choose the material of your choice and accordingly you can choose the separation between the target material and the detector within the particle accelerator beam hall.

So, if I consider the charger particles like alpha particles protons electrons or heavy ions then the important topic is linear stopping power for charged particles that is as energy loss per unit length which is also called as specific energy loss and the standard Bethe-Block formula - da by dx is this pi is a constant the charge this is the incident particle z and velocity of the particle and number density.

And where this B is given as this atomic number of the matter with which radiation is interacting and remaining terms are well known. So, using this one can find out the energy lost per unit length and here you can see the specific energy loss in air MeV per centimetre with respect to particle energy. What kind of particles we have considered here alpha particles, protons, electrons.



Interaction of radiation with matter

Linear stopping power S for charged particles $S = -\frac{dE}{dx}$ specific energy loss

Bethe formula $-\frac{dE}{dx} = \frac{4\pi e^4 z^2}{m_0 v^2} NB$ $B \equiv Z\left[\ln\frac{2m_0 v^2}{I} - \ln\left(1 - \frac{v^2}{c^2}\right) - \frac{v^2}{c^2}\right]$

So, here for nuclear astrophysics we are mainly interested in the protons and alpha particles. So, one can get the information of this with the help of SRIM that means stopping power and range in matter or using different types of codes also one can find out this specific energy loss and when you see with respect to distance of penetration, we call this as a Bragg curve. And for single particle you can see how it looks like and for parallel beam because of a phenomenon called as straggling you will get this kind of response.

And if you plot specific energy loss with respect to energy for helium ions in copper, helium 3 ions in aluminium and alpha helium 4 in nitrogen then how the specific energy loss looks like. So, you can see in this diagram. So, in the next lecture I will explain the interaction of gamma and neutron with matter. Thank you for your attention.