Nuclear Astrophysics

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Lecture – 35

Detectors – I

Welcome students continuing the discussion on nuclear radiation detectors in today's lecture. So, what did we discuss in the last class. The role of contaminants in hampering the studies of nuclear reactions and how to avoid them like carbon 13 is one of the important contaminant by reacting with alpha beam it can give neutrons and these neutrons can further give gamma rays. So, which contributes to the detector background and oxidation onto the target materials and another important contaminant is a hygroscopic nature can spoil the composition of the target material. So, by heating the system in a proper environment so, one can clean the contaminants and sometimes by passing the carbon content which develops in front of the target material through liquid nitrogen metal tube also one can get rid of the contaminants all right.

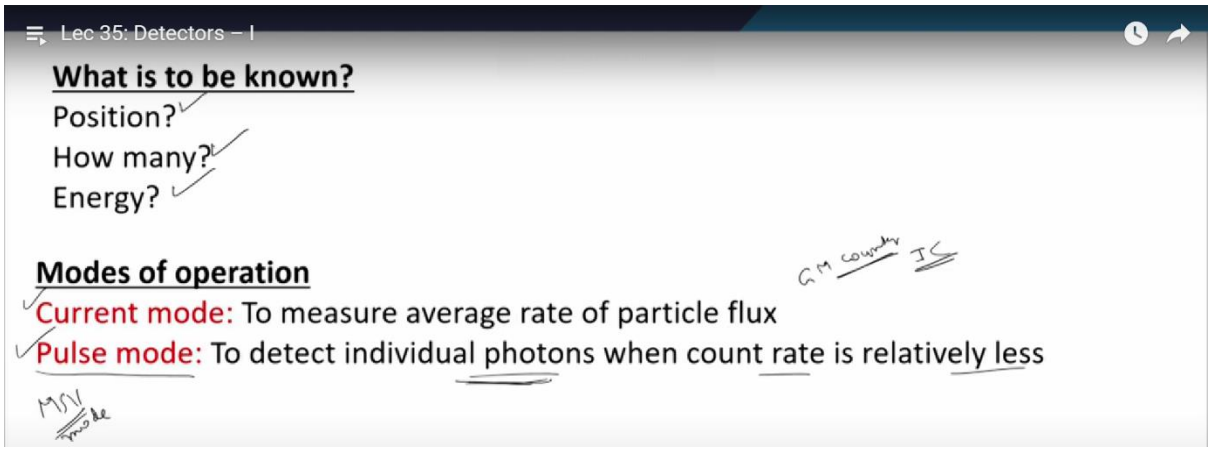
So, after that we started seeing the radioactive sources I have discussed the decay schemes of a few gamma sources one neutron source that is californium 252 and alpha source Americium 241. So, it is very important to understand the decay schemes of radioactive sources in order to properly test the performance of any nuclear radiation detectors. I just started the interaction of radiation with matter in the previous lecture and I have covered interaction of charged particle with matter.

So, that comes under recap and then more about the detectors I will discuss in today's lecture. So, what is the purpose of nuclear radiation detectors for nuclear astrophysics the measurement of cross section depends on the measurement of yield of the nuclear reaction and yield measurement can be done only with the help of nuclear radiation detectors. And if you are measuring the yield the nuclear reaction by detecting the neutrons you have to go further neutron detectors if you want to measure the yield of the reaction in terms of gamma you use the gamma detectors.

So, what should be the choice regarding the detectors what are the considerations what are the ideal properties what types of detectors are preferred for experimental nuclear physics. Let us try to understand in today's lecture. But I am going to cover the basic part of the detectors which will be useful to understand the response of the detectors when you carry out nuclear reactions relevant for astrophysics all right.

In any nuclear reaction what should be known? What is the position of the interaction sometimes you want to see this and many times of course most of the times you want to see the how many particles are emitted from the nuclear reaction and then what is the energy of the particle emitted during the nuclear reaction. And in how many ways, in how many modes

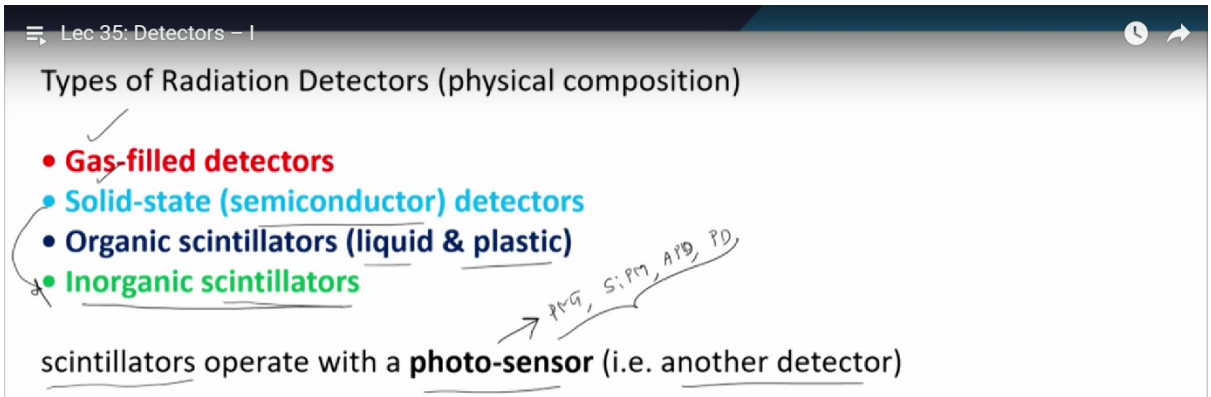
the detector can work in general we can divide into three types that is current mode pulse mode and there is mean square voltage mode that is not very useful for our purpose.



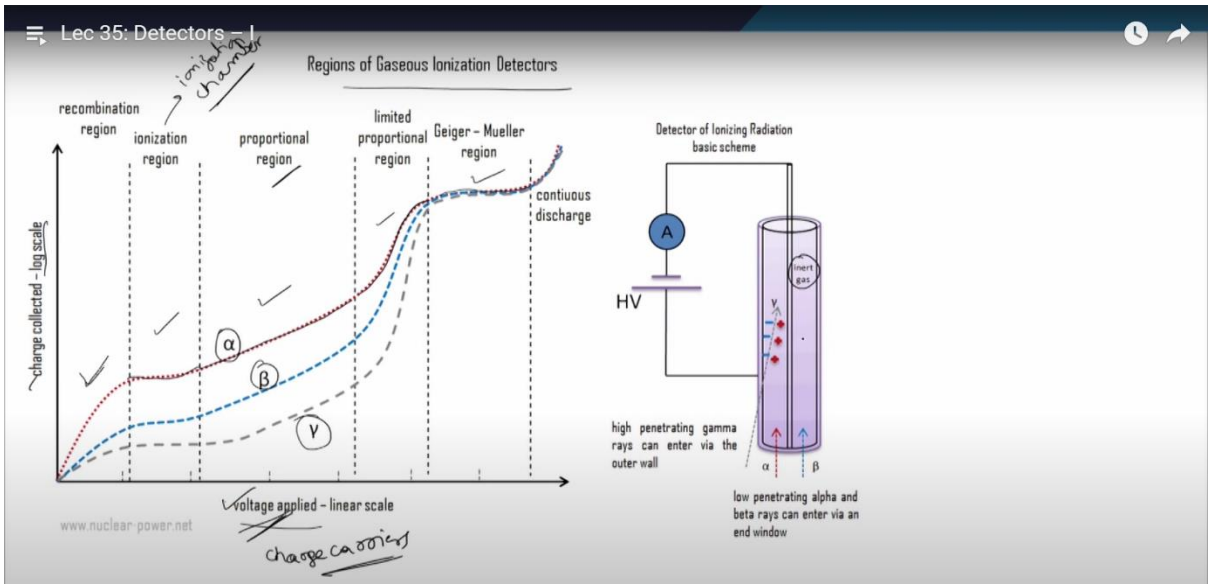
So, in even for nucleus physics normally we prefer pulse mode. So, in the current mode normally we try to measure the average rate of particle flux this is used basically for example if you go for GM counter or ionization chamber you can use in the current mode to know the average rate of particle flux. And when count rate is relatively less and when you detect the individual photons or any other particle and if we want to measure the energy then one has to go for the pulse mode.

How many types of radiation detectors are available in terms of physical composition one can have the gas as the detection medium one can has the solid for example semiconductor detector and then organic scintillators either liquid or in plastic or inorganic scintillators of course this also comes under the solid state. However inorganic scintillators are separated from the solid state just to differentiate from the semiconductor detectors.

Otherwise inorganic integrators they are also solid materials the detection medium is solid material. Mainly we prefer scintillators for the detection of gamma rays. And many times for the neutrons as well which operate with a photo sensor. Because material which scintillates that is the material which gives photons in visible region they are called as scintillators and to detect these scintillations that means optical photons one need to use the optical photo sensor.



One can use a photo multiplier tube or one can go for silicon photo multiplier one can go for avalanche photo diode one could go for a simple photodiode. So, there are different types of photo sensors which itself is a detector of optical photons emitted by scintillation material.



So, let me start with the gas detectors hope you have been taught in your B.Sc. The gas filled ionization detectors which works in different regions like recombination, ionization, proportional, limited proportional and Geiger Muller region. If you plot this collected charge and the applied voltage this is in linear scale and this is in log scale.

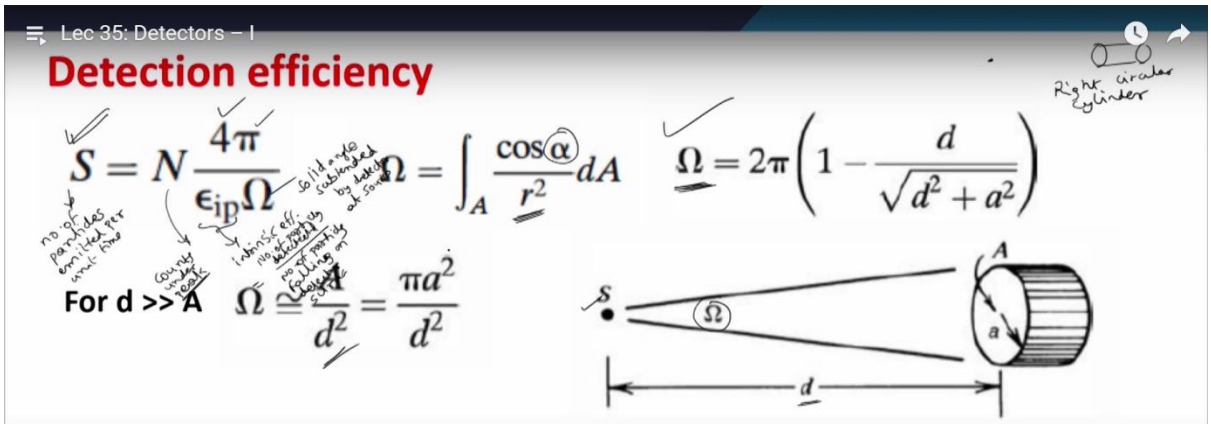
Initially when because of the ionization and excitation charge carriers are created under the influence of electric field which is generated because of the applied voltage. The applied voltage causes the electric field to exist in the active volume of the detector. In the presence of electric field the charge carriers will undergo drift and when electric field is quite small which is not sufficient for the charge carriers to get collected respective electrodes then they will recombine.

So, that is what I am saying in the first region recombination region charge carriers will be formed and they will be recombined. Of course, the probability of recombination will decrease as electric field increases. So, slowly it reaches to a saturation kind of thing and once the recombination becomes almost zero. Then the region up to which the charge collector remains same is called as ionization region.

A detector working in this region can be called as ionization chamber and sometimes as part of advanced instrumentation in nuclear astrophysics researchers are using segmented ionization chambers. So, when you come across ionization chamber it means a detector which works in the ionization region where the charge collected is saturated it is constant with respect to the voltage.

But will it be same always? No after certain electric field there is a process which starts developing within the active volume that is the multiplication which reaches to the proportional region. So, this linearity in the increase of charge corrected corresponds to the proportional region. And once this linearity gets disturbed you are entering into the limited proportional region.

And after that there is no relation between the incident energy and the number of charging carriers are corrected because of the avalanche which gives rise to Geiger Muller region. And how these characteristics of gas field detectors looks like for alpha, for beta, for gamma, you can see in this diagram. So, this is the schematic of the ionization detector. So, there is an inert gas we take normally. So, any radiation when deposits energy.



So, they will cause ionization and excitation and under the influence of electric field the collection of charging carriers takes place.

How to find out the efficiency of a detector. Of course, when we use any detector in the nuclear reaction we prefer to use the detector of high efficiency. So, let us see the basics of detection efficiency and once you know the detection efficiency many times you can find out the activity of the radioactive source also. Do you remember in the previous lecture I have discussed decay schemes of several radioactive sources caesium, cobalt, sodium.

And I am confining my discussion to the gamma rays in this particular case when the source emits gamma rays in different directions what is the number of gamma rays per unit time what is activity here I am representing using the symbol S.

So, S is basically number of particles emitted per unit time all right and N is the counts under peak of the spectrum, pi is a constant, four is a constant and this is the intrinsic photo peak efficiency. That means number of particles detected under peak divided by number of particles falling on the surface omega is the solid angle subtended by the detector at the source which is given by.

What is the solid angle subtended by the detector surface. Of course, it depends on the distance between the source and detector. So, you have to integrate the detector surface area over the distance between the source ion detector and where alpha is the angle between the normal of the area element and the source point and here for a common case of source and if you have a right circular cylinder.

This is for right circular cylinder we can write down the solid angle as 2 pi into 1 - d by d square root of d plus s square. Here you have the source, you have the right circular cylinder the distance between source and directory is d, omega is the solid angle subtended by the detector at the source and small a is the radius of the detector front surface. A is the area of the detector front surface.

If this distance is much greater than the area of the detector front surface then this solid angle can be approximated as area divided by d square and this area is nothing but pi into square of the radius of the detector front surface.

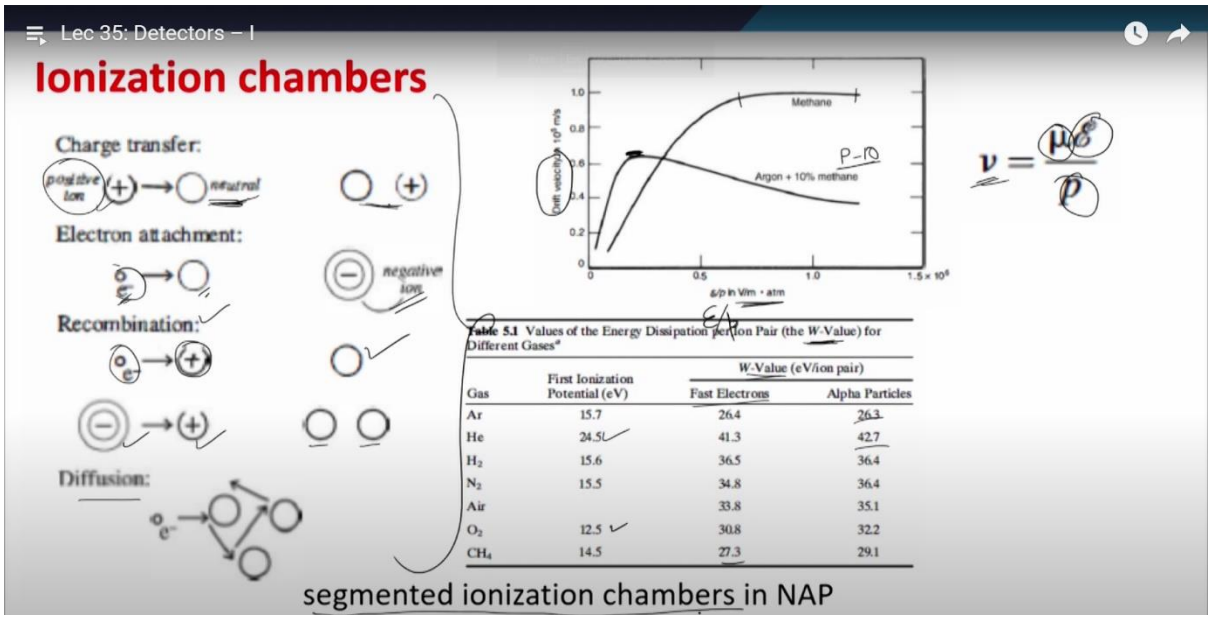


Table 5.1 Values of the Energy Dissipation per Ion Pair (the W-Value) for Different Gases[a]

Gas	First Ionization Potential (eV)	W-Value (eV/ion pair)	
		Fast Electrons	Alpha Particles
Ar	15.7	26.4	26.3
He	24.5	41.3	42.7
H_2	15.6	36.5	36.4
N_2	15.5	34.8	36.4
Air		33.8	35.1
O_2	12.5	30.8	32.2
CH_4	14.5	27.3	29.1

Now let us see more about the ionization chambers. When charge carriers are created how many types of reactions can happen. See in the gas medium when positive ion is created it can always transfer its charges to some neutral atom or molecule and charge transfer can take place.

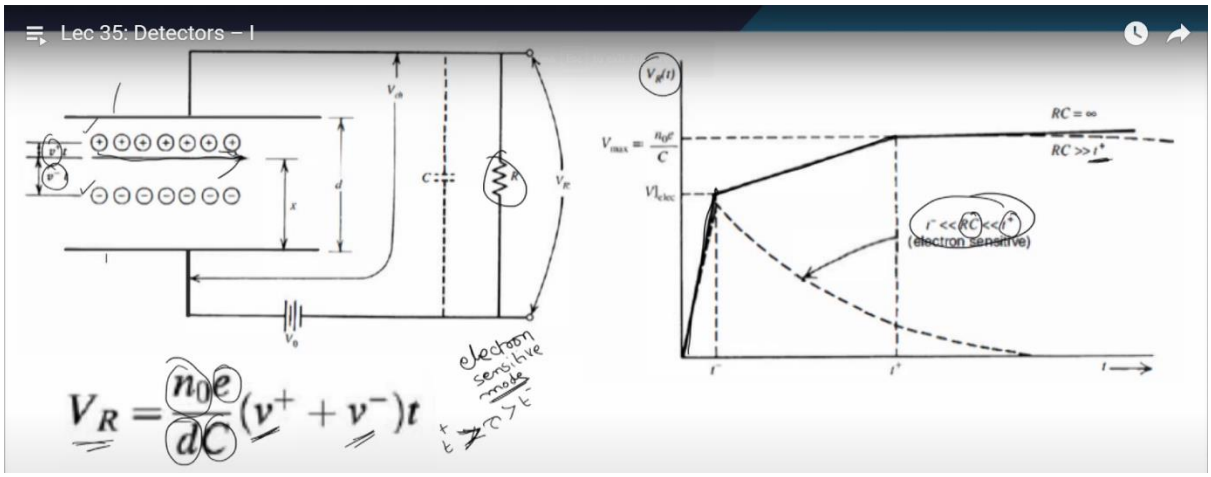
And sometimes electron attachment can happen. So, this electron and positive ion they have been created because of the ionization and excitation within the gas medium by the incident charged particle. So, electron can undergo attachment with the atom or molecule and positive ion also can undergo attachment with the atom or molecule of the gas. So, then you have negative ion in this case and the recombination also can happen that is the first region if the probability is more.

So, electron positive ion can give rise to some neutral and sometimes the negative ion can react with the positive ion gives rise to two neutral one and diffusion also can happen when atoms are molecularly considered how the diffusion of electron takes place. So, all these processes are possible within the gas medium how much pressure should be applied how to choose the pressure of the gas.

So, that it can be used as a proper detector one of the important considerations is the drift velocity of the charge carriers should be almost constant when there is a change in the electric field even though you maintain the voltage constant that means electric field is a constant small change in electric field sometimes can cause big change in drift velocity.

Change in the drift velocities can gives rise to change in the collection times and change in the collection times can gives rise to change in the pulse height. Change in the pulse heights can gives rise to huge error in the energy measurement. So, that is how it will hamper our purpose of the nuclear reaction. So, it is important to choose proper electric field when gas medium is used in the detector.

The criteria is following electric field divided by pressure in voltage meter atmosphere may be this is not visible. So, I am writing for you clearly electric field divide the pressure on x axis drift velocity in 10 to the power of 5 meters per second. So, normally used gas is P10 which is 90% argon 10% methane and normally this is chosen here the drift velocity is constant and if methane is used of course you can use 0.6 to say 1.2 volt per meters atmospheres.



And the drift velocity is given by the mobility of the charge carrier electric field and the pressure of the gas. And just for your information this table gives you values of energy dissipation per ion pair which we use where we use the symbol W energy required to produce one electron ion pair in case of gas or one electron hole pair in case of semiconductor or scintillator material that is called as W value.

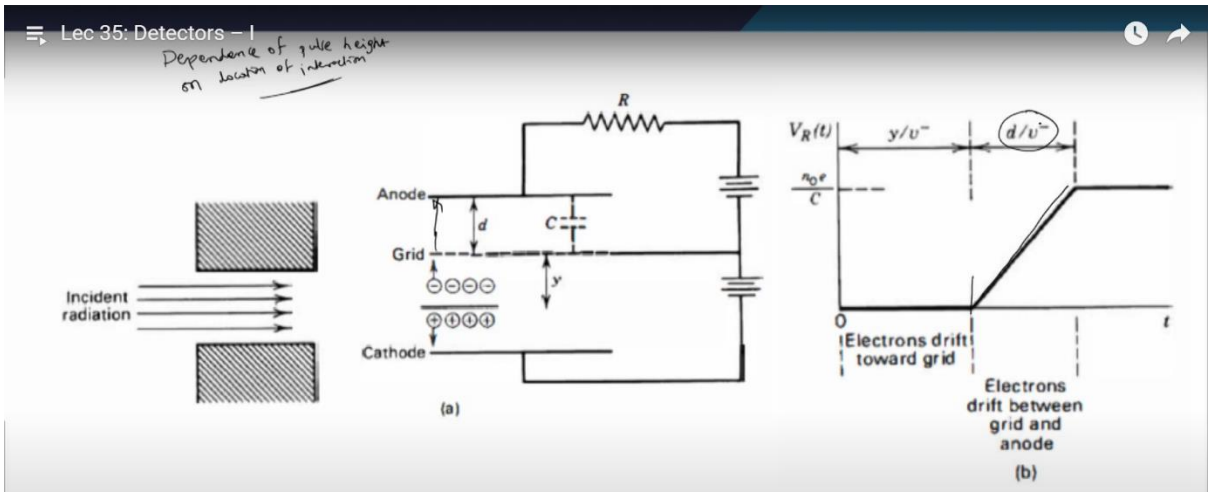
More W value less number of charge carriers for a fixed incident energy and for a fixed incident energy lesser the value of W larger will be the number of carriers. So, that is where semiconductor detectors are preferred over ionization chambers for the detection of charged particles. So, you can see the first ionization potential is ranging from say 12.5 to 24.5 electron volt.

The W value for fast electron it ranges from say 27 to 41 and for alpha particles this is of our interest ranges from 26 to 42.7, electron volt per ion pair. So, if you know the w value you can find out the number of charge carriers produced for the fixed instant energy and that helps us in getting the information of pulse height. In nuclear astrophysics as part of advanced instrumentation people are using a segmented ionization chamber. And in this slide I have discussed the salient features of basic ionization chamber.

Let me discuss the simplest design of the ionization chamber two electrode parallel plate ionization chamber where this arrow mark denotes the travel of charged particle within the gas and just for the sake of convenience this positive and negative charge carriers they are represented on both sides and they are corrected at the respective electrodes. Electrons are collected at the anode and the positive ions are collected at the cathode material.

And they have their velocities with respect I mean which depends on the electric field within the gas medium and the voltage across the load resistance is given by number of charged carriers produced the value of charge separation between the plates capacitance which includes the stray capacitance of the detector and the velocity of the positive ions well as to the negative

particles that is electrons. Positive ions are 1000 times heavier than around thousand times heavier than the electrons.



So, it will take less time to reach the electrode. Electrons being lighter particles it will quickly collect at the anode. So, electron will reach the electrode first that is the reason many a times ionization chambers are operated in electron sensitive mode. The time constant of the detector circuit is chosen such that it is less than the collection time of positive ions but I mean tau is less than the t plus but greater than t minus that is collection time of the electrons.

So, it will not consider the motion of the positive ions otherwise it is difficult to maintain the count rate. And this is how the time development of voltage pulse across the load resistance takes place time on x axis voltage development across the load resistance on y axis. So, up to this electrons motion positive ions motion see after electrons are collected you have. So, much time for the positive ends to get collected.

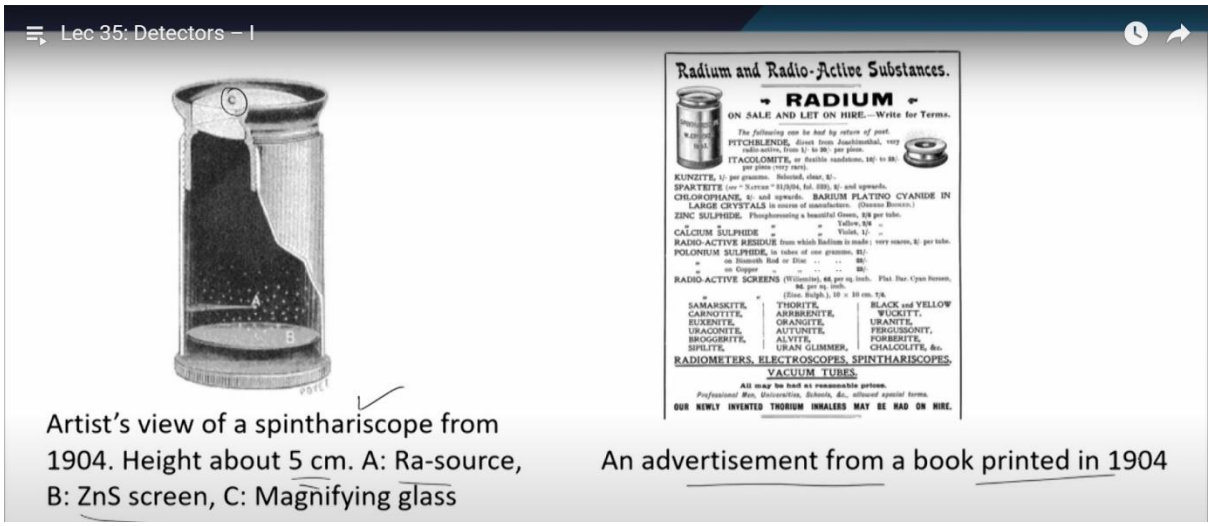
So, that is the reason here I have said t minus is less than time constant of the detector circuit and this is much less than the t plus electron sensitive mode. If the time constant is chosen much larger than the t plus then positive ions collection is also considered. So, this is how time development of voltage pulse can be calculated using conservation of energy one can derive the formula.

Now the problem in parallel plate ionization chamber is the dependence of pulse height on the location of interaction. So, this is a very important phenomenon the dependence of pulse height on location of interaction. So, depending on the location interaction if the pulse height changes then the energy measurement will be difficult for this given energy pulse height is different two same energies two particles of same energies will give two different pulse height.

In the case of two parallel plate ionisation chamber but in this particular case we want the energy should be same as was the original that is the reason grid is introduced between the two plates and the location is confined between the grid and the cathode. So, that electron wherever they are created once they started moving towards the anode it will not be considered for the pulse formation until it crosses the grid.

Here the distance between the anode and grid is taken as d. So, this diagram helps us how to understand the pulse formation till electron drifts toward the grid there is no pulse development

and the pulse starts developing after this position. So, d by v minus gives you the collection time of the electrons all right.



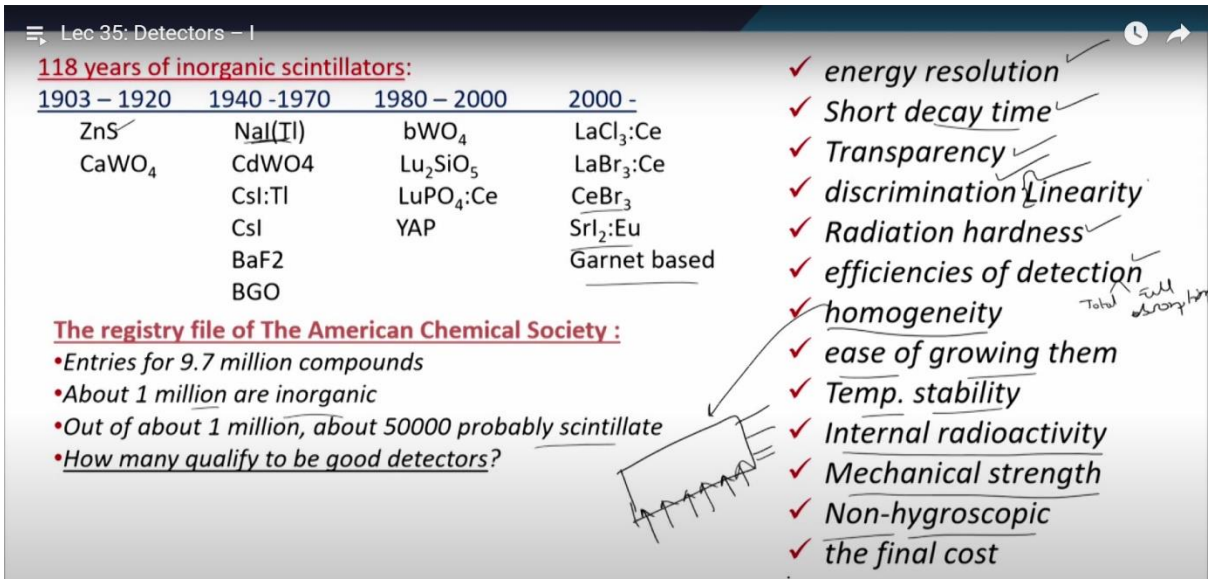
Then let me discuss the scintillation detectors the story starts from the spinthariscope. Where about 5 centimetre height and radium source was used for the alpha particles zinc sulphide screen and here the magnifying lens is used with the naked eye people use it to count the scintillations. And one interesting advertisement from a book printed in 1904 you can see here and the details can be found in this paper.

If you see the evolution of inorganic scintillators starting from the zinc sulphide now we have come up a long way. So, starting from time tested sodium iodide people are widely using advanced scintillators like lanthanum halide, cerium bromide, strontium iodide and garnet based scintillators. If you see some numbers interestingly around 10 million compounds are entered in the American Chemical Society Registry.

And out of them one million compounds are inorganic out of them probably 50000 will scintillate but the question is out of them how many will probably scintillate. So, that is a challenge and what are the properties that we look forward to when we consider any scintillation detector. So, after discussing gas based detectors I am discussing now the scintillation detectors.

So, that is energy resolution the ability to resolve two energies closely separated from each other. If fast timing is preferred we of course look forward the fluorescence phenomenon should happen very quickly. So, we should have a short decay time and then it should be transparent to the optical photons generated within the scintillator and discrimination of different types of radiation. Linearity of the detector that means the relation between energy and the pulse height should be linear. So, this linearity of the detector can be checked by considering energies of gamma rays by taking different values and how hard it is with respect to radiation can it sustain the high amount of radiation for long time and then what is the ability to detect which can be categorized into total detection efficiency and full absorption efficiency. Homogeneity what is this homogeneity if I consider any detector. If gamma has come through here through here through here see the PMT is placed here. So, if gamma is falling at any point from the side then the performance should not be much different from each other. So, normally

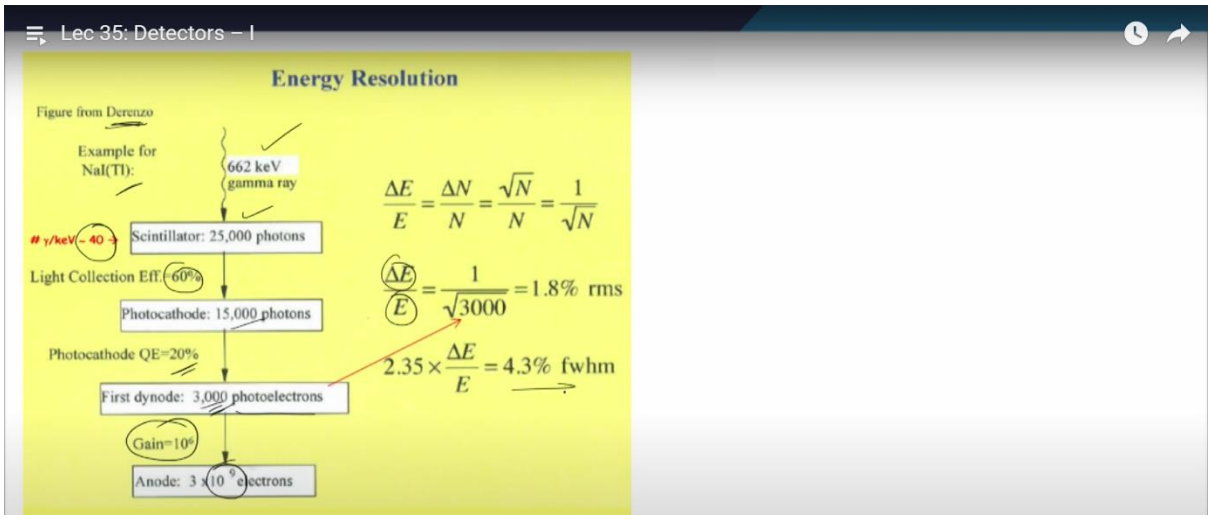
we call this as lapping also. So, homogeneity also has to be checked for the large volume detector and how easy it is to grow in large volume.



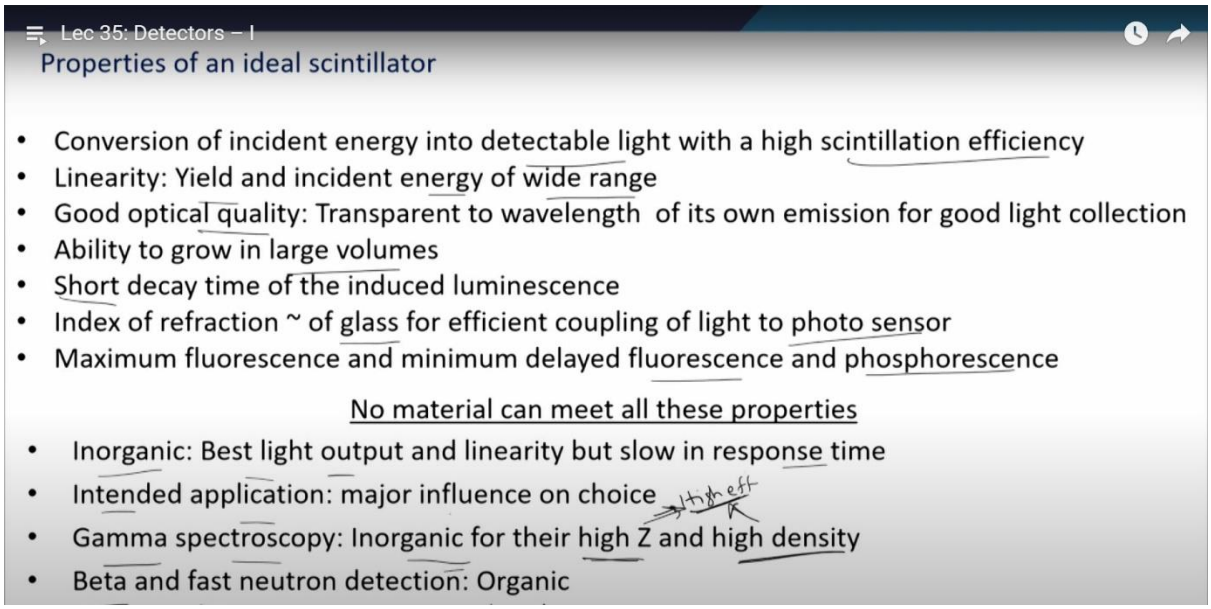
And how, stable it is in terms of temperature of course not much relevant for nuclear astrophysics because we are not operating these detectors at the very low temperatures though it has its own advantages. Detector should not contribute to a radioactivity from own. So, detector should not contribute to the radioactivity otherwise the count rate that we are looking for will be overlapped with the reaction products of the nuclear reaction.

So, how good it is in terms of mechanical strength whether it is hygroscopic or non-hygroscopic if it is hygroscopic you have to encase in some aluminium kind of caning and then of course the final cost. So, all these parameters comes into picture when we decide any scintillation detector.

Let me give you one simple example regarding the energy resolution which is the first property I mentioned in the previous slide. So, you can see here example for the sodium iodide if you take. So, 662 keV gamma if you consider it will emit 25000 photons considering the per keV 40 number if you consider and if the light collection efficiency is 60%.



Then so many photons will reach the photocathode and the photocathode quantum efficiency if it is 20%. Then how many photoelectrons are emitted 3000 and considering that gain of the pmt is 10^6 then at the anode you are getting 10^9 electrons. And here this 1 by square root of N 3000 is giving rise to delta E by E and multiplying with 2.35 you are getting 4.3% of full width at half maximum.

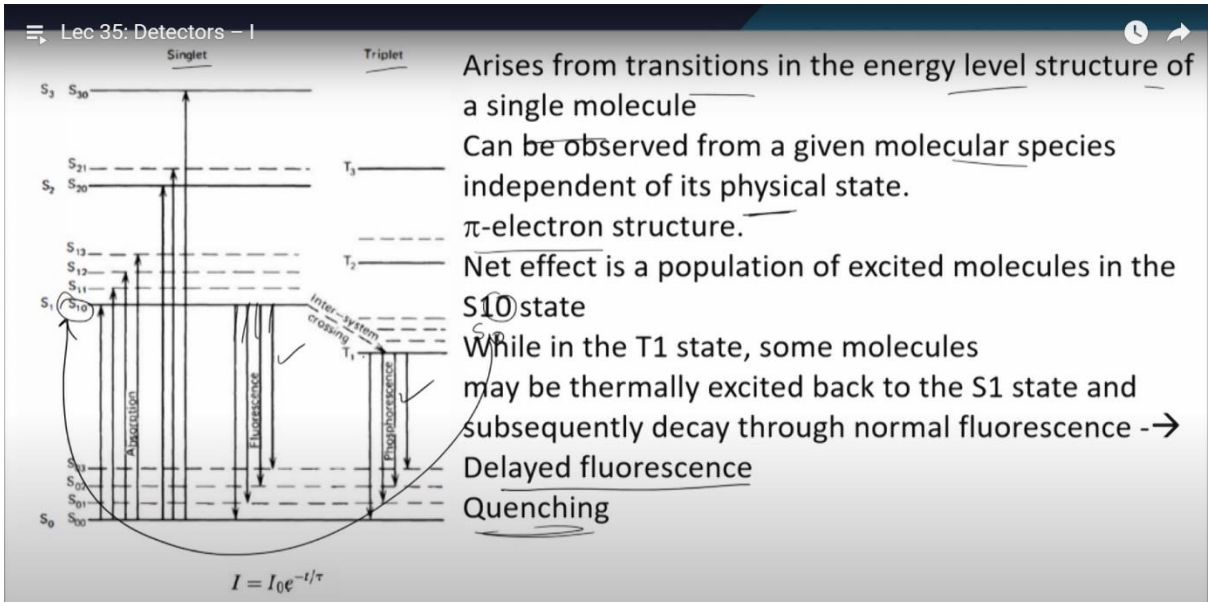


And what are the properties of an ideal scintillator it should be able to convert the incident energy into detectable light with high scintillation efficiency and as I said linearity, yield and incident energy of wide range should be linearly related and optical quality should be very good otherwise whatever optical photons are created they will be absorbed within the crystal. And one should be able to grow in large sizes decay time also should be very less.

The refractive index should be in such a way that it should be matching with the glass. So, that coupling can be efficient when we couple the scintillation crystal to the photo sensor and fluorescence should be maximum and minimum delay fluorescence and phosphorescence should be very less and of course there is no material which can satisfy all these properties. So, there is a trade-off between the properties and depending on the application and available resources one should choose the scintillation detector.

And if we consider inorganic they are best in terms of light output and linearity but the problem is they are not very fast. So, the intended application decides the major influence on the choice. And for gamma spectroscopy mainly we prefer inorganic detectors. Of course we also use the semiconductor detector and when we use inorganic detectors the main reason is for high z which gives rise to high efficiency of detection and the high density and high atomic Z they lead to the high detection efficiency.

And for normally for detecting the beta and fast neutrons we use the organic because considering the nature of interaction of beta and neutrons we prefer the organic molecules which normally contains hydrocarbons. And the interaction of this neutrons with the hydrocarbons leads to better nuclear reaction probability.



And this is how organic scintillator works you have singlet states and triplet states the transition after following the excitation which gives us the fluorescence. So, it arranges from the transitions in the energy level structure of the single molecule and it can be observed from the given molecular species which is independent of its physical state that is the interesting point in the case of organic scintillators and it has so, called the pi electron structure.

And the net effect of this transition is the population of excited molecules in the S10 state this is the S10 state. So, this is basically S10 state you can see the transitions are taking place mainly from here only. And where in the t1 state some molecules may be thermally excited back to the s1 state. So, here instead of transition happening here it can go from s states to singular to triplet. This goes to the phosphorescence and sometimes it can go from this t states to a states again gives us to delayed fluorescence. Quenching is an interesting phenomenon in the case of organic scintillators and scintillation time profile can be understood with the help of this equation. And the property which is interesting in the case of organic scintillators is the absorption and emission the peaks corresponding they are separated by some distance when you plot absorption emission intensity with respect to wavelength which we call as strokes shift. So, in this lecture we have discussed about the ideal properties of scintillators something about organic scintillators and ionization chambers and characteristics of gas field detectors.

In the next lecture I will discuss some more content related to the response of detectors for gamma rays and neutrons, thank you so much.