Principles of radiation detectors

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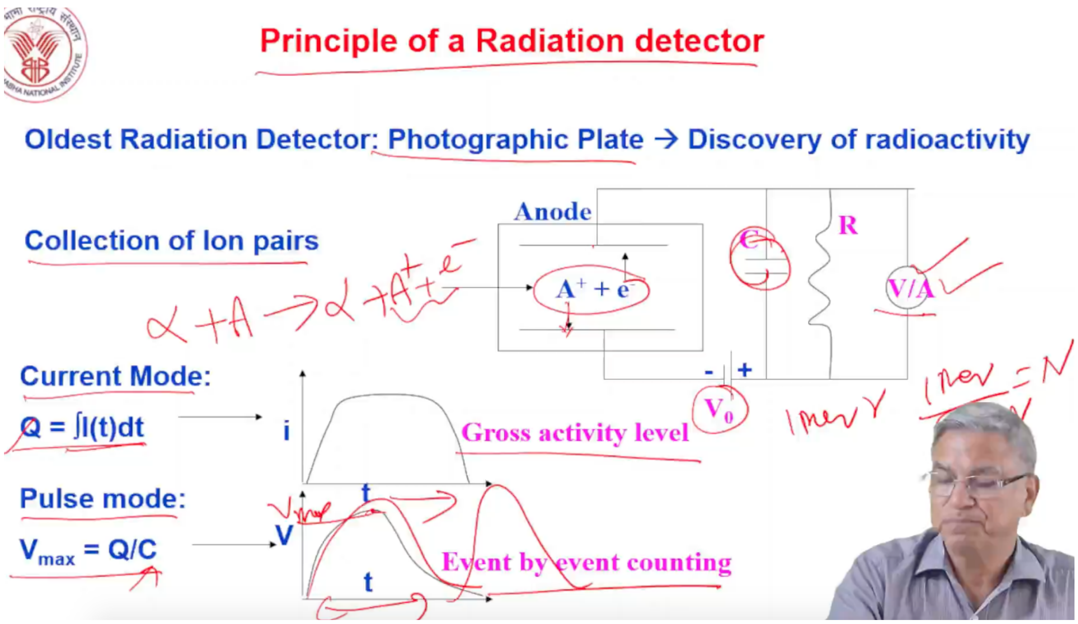
Lecture-9, module-1

Dear students, so we just discussed the interaction of different types of radiations with matter, like heavy charged particles, alpha, protons, light charged particles or fast electrons, neutral particles, gamma rays and neutrons. These are the types of radiations that one will be encountering while working in a radioactive area. So this interaction of different radiations with matter helps in developing detectors when you want to choose a detector for a particular radiation. So that knowledge will help in understanding the principle of different radiation detectors. Before we go to the actual detectors, different types of detectors that we will be discussing in today's this lecture, I want to discuss the basic principles of radiation detectors. So how do we get a signal from a detector? Detector will sense the gamma ray or the alpha or beta or electron.



Principle of a Radiation detector

Oldest Radiation Detector: Photographic Plate → Discovery of radioactivity

Collection of Ion pairs

Current Mode:

$Q = \int I(t)dt$

Pulse mode:

$V_{max} = Q/C$

So how do we get the signal from detector? That is what we try to understand. So all of you know that Henry Becquerel discovered radioactivity simply using a photographic plate. So in essence, a photographic plate is also a detector. One of the oldest detectors is a photographic plate, but that will give you a qualitative picture.

So when we want to go for quantification of radiation levels, we use advanced detector systems and so the basic principle of detection of radiation is collection of ion pairs. If you recall your discussion on the interaction of heavy charged particles, the heavy charged particles cause ionization. It can also cause excitation, but the ionization will give you ion pairs. And if you collect the ion pairs, you can detect the signal. The electrons also give you ion pairs.

Similarly, the gamma ray by secondary means will give us electrons by photoelectric effect or even Compton scattering or pair production. The neutrons also give rise to heavy charged particles by way of nuclear reactions. So the net result of all types of interactions of this ionizing radiation is the production of ion pairs. So if a radiation is passing through matter, it will give,

$\alpha + A \rightarrow \alpha + A^+ + e^-$

So if you can collect this electron and positive ion at the respective electrodes, you can get the signal.

So this is a schematic of a detector. If you collect the electrons at the anode and the positive ions at the cathode by applying the potential at the anode. And so you essentially you are charging the capacitor, the electrons will be charging the capacitor and when the capacitor is fully charged, it can discharge through a load resistance R and the discharge of the resistor you can measure in terms of a voltage or current. So you can use a detector in current mode, if you put an ammeter here or you can put a voltmeter to get the pulse. So we'll discuss both the mechanisms and see also their merits and demerits.

So when you measure the current in this circuit, then whatever charge was created by interaction of radiation with matter, the total charge, what is the total charge? So suppose you have 1 MeV, gamma ray. So it will be giving 1 MeV energy. How many ion pairs it will produce? So this is the energy required to produce 1 ion pair, W electron volt, 1 MeV, so you will get N number of ion pairs. So these ion pairs are collected and that's why essentially you are collecting the charge, that is what is this charge. Now when this charge is discharging through an ammeter, then capacitor is discharging through an ammeter, you see the current flowing in the circuit.

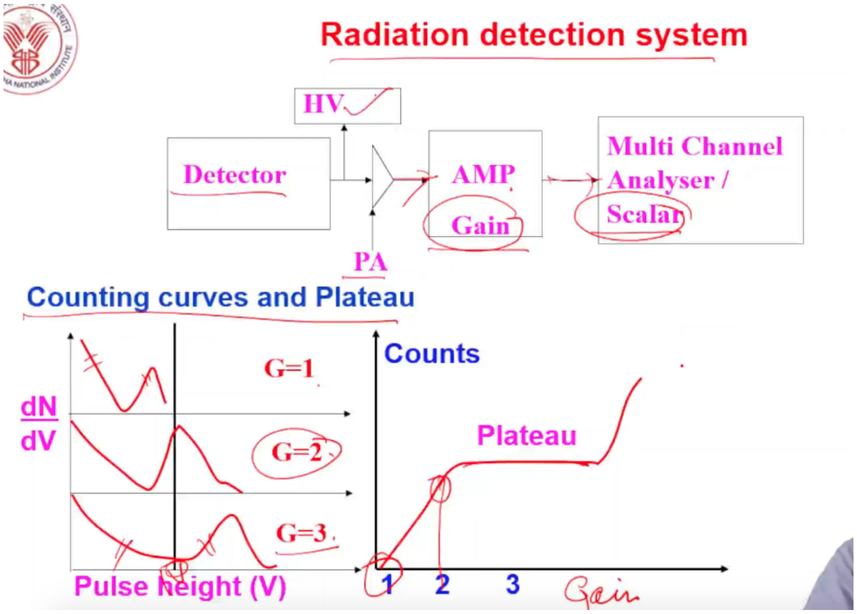
And what you see here in the time domain, you see the current is, it will be rising, become flat and come down. So one event will be like this and then there will be several other events. So multiple events will lead to a flow of current in the circuit. Because of that, there will be a constant current flowing in the circuit, this mechanism of current mode is not suitable for the counting of the activity, but it gives you the gross activity level. Like you have a survey meter in the laboratory, just you want to know what the level of radiation you can use for gross activity counting current mode.

It is giving you a current level, how many microamps, how many nanoamps, how many milliamps, that tells you that this is the level of radiation. But if you want to count the activity, how many counts per second, quantitatively you want to know, then you require pulse. So you need to shape the pulse. So what do you do? Whatever charge is produced Q, you get a voltage at the voltmeter Q/C. So the maximum that voltage will is Q/C, the capacitance of the circuit.

Actually, this capacitance is not only this capacitor, but the detector system also will have its own capacitance. Net capacitance of the detector system is involved in determining the voltage. So the voltage will rise, go to maximum and it will fall down. So this is the V_{max}. And the rise and fall will depend upon the C and R.

This is called CR circuit. In fact, the detector systems have a series of CR-RC circuits and you play with the circuitry to get a proper signal. Essentially, we want to get a voltage signal. If you see in oscilloscope, the voltage signal will rise. This will rise and fall down.

And it should fall down before another event comes so that they can be separated. And so you can count. So we will discuss about the dead time and all. So different individual pulses are counted in the detectors in the pulse mode. And that pulse mode then is used for event by event counting. Each decay you can count separately in the pulse. So the detectors actually are operated in current mode and pulse mode. Some detectors are used in current mode also like survey meters where you are interested in only gross activity level. But whenever you want to measure each event separately, then you use pulse mode.



Radiation detection system

Counting curves and Plateau

So this is a block diagram of a radiation detection system. You have a detector. It can be gas, solid, liquid. And you have to apply some potential. Somewhere ago the charged particles have to be collected at anodes and cathodes. So you apply the high voltage at the anode. And then once Q, the charge that is collected, you have to get a signal.

So the preamplifier does the job of getting a voltage signal or a current signal from the detector system. And the preamplifier actually just giving a initial signal which have a low output impedance. Normally detector output impedance is very high. It will get attenuated. So you use a preamplifier to decrease the impedance of the output signal.

And subsequently you can carry it to long distance and then there is an amplifier which will amplify the signal to a measurable range of 0 to 10 volt or whatever it is. And these pulses are then fed to a counting system, multi-channel analyzer. You have 4096 channels or you can use timer scalar. You can count in the scalar mode or you can generate a spectrum in the multi-channel analyzer called MCA.

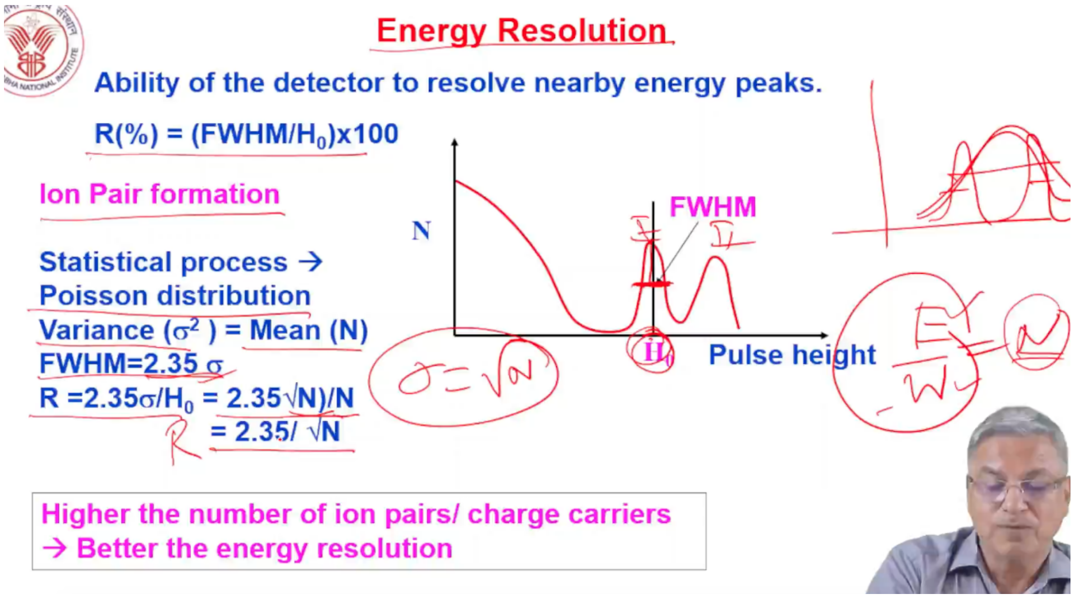
So this is a schematic of a particular detector system. You have a detector material. We'll discuss the details of detectors separately. You need a high voltage, you need a preamplifier, amplifier and the multi-channel analyzer or scalar. Now whenever we want to set up a detector system, we should make sure that detector is functioning in a stable manner.

The settings of the detector should be proper. And so that is why we need to generate these counting curves and plateau. So counting curve and plateau means what? Whenever you are counting, detector is giving you proper results.

So there is a quantity called gain. Gain means your amplification factor. So in the amplification, what is the extent of amplification you have to do so that you're counting the signal and not the noise. So I try to illustrate this using this figure here. What I have done here, the gain, the gain is like one, two, three different types of gain, the pulse height. So here is a pulse height distribution (PHD). So you have a time at the voltage versus the counts, the dN/dV, number of pulses of a particular height.

Now what happens initially, suppose you have got a low gain in the amplifier. Then you put a threshold in your timer scalar or a multilayer analyzer, you have a threshold, let us say one volt. Any pulses above one volt will be counted. It is below one volt, it will not be counted. So this is the threshold for, let us say one volt. So anything beyond this only will be counted. Now at low gain, you can see the noise and the pulse, both are below the threshold. So you will not get anything, no counts. So this is the gain versus counts. Then you slightly increase the gain, G=2. And now you can see the pulse is stretched to the higher pulse height, but still you see some part of the pulse is still below the threshold. So you will get this rising part somewhere here, but not complete, all pulses are not above the threshold. Then you further increase the gain to the third one and here noise is below the threshold, but the actual, all the pulses are above the threshold. So this is what is the plateau. And if you further increase the gain, then you will find even the noise will go beyond the threshold and there will be a rise in the counts, so this is the plateau region where you have to set up, do the settings.

You can operate at this particular gain. In many detectors like Geiger-Muller counter, NaI(Tl), you can change the gain of the detectors system by high voltage. So many times in GM counter, instead of gain, you change the high voltage and find out the high voltage at which the detector, the system is stable. So this plateau and counting curves are actually used in the GM counter very routinely to set up the high voltage, which you have to apply so that the detector system is functioning properly. So counting curves and plateaus are very important for setting up a detector, which will give reliable results and it will be stable system.



Energy Resolution

Ability of the detector to resolve nearby energy peaks.

$R(\%) = (FWHM/H_0)x100$

Ion Pair formation

Statistical process → Poisson distribution

Variance (σ^2) = Mean (N)

FWHM=2.35 σ

$R = 2.35\sigma/H_0 = 2.35\sqrt{N})/N$

$= 2.35/ \sqrt{N}$

$\sigma = \sqrt{N}$

Higher the number of ion pairs/ charge carriers → Better the energy resolution

Another important property of detector is the energy resolution. I have discussed the general property of detectors so that we don't have to repeat it every time. So what is the energy resolution? So a source may be emitting different radiations, different gamma rays of different energy, whether the detector can resolve those that will depend upon the energy resolution. For the ability of a detector to resolve nearby peaks, we call it the energy resolution.

Just to illustrate here, suppose there are two peaks, one and two. These two peaks are nearby. So if our resolution is good, they will appear as separate peaks. But if the resolution is poor, it can appear like this also. So it could be like this, but it could be broad. So poor resolution and good resolution. This is what we want to mean. So you have to see that the resolution is low. So when you say better resolution, the R value, the R value, how it is defined? R is the resolution in percentage. Normally when you see the pulses, pulse height spectra, they will appear like a Gaussian for a single peak and the full width at half maximum (FWHM) of a Gaussian. So FWHM, when the counts become half, the width at that time is called full width at half maximum upon the mean value of the pulse height,

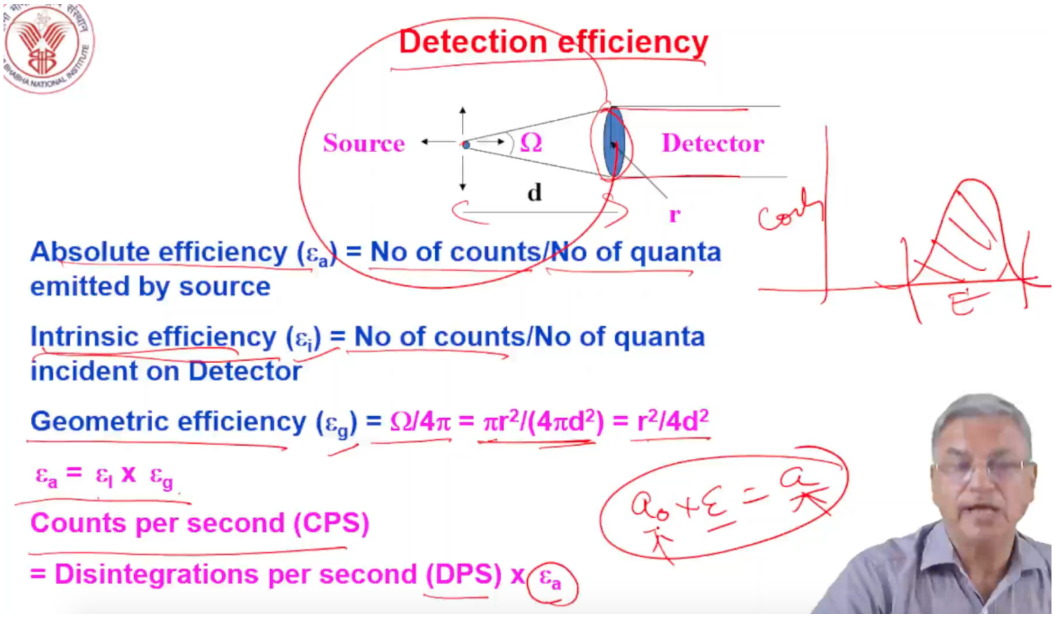
$R(\%) = (FWHM/H_0)\times100$

They have the same unit, this and this have the same unit in terms of percentage.

So this is how we define the resolution. So lower the value of R, better is the resolution. So FWHM has to be low, as low as possible. So now let us go a little more details of the how do we define this resolution and how we can improve this resolution. So when the radiation is falling on a detector system, we cannot define a priori how many ion pairs will be created. Though we say E/W is the number of ion pairs (N). Every time a single energy photon interacts or the alpha particle interacts, it will not give the same value of N. Though energy is constant, W value is at the average energy. But N is not constant. So this is a statistical process. You will say random fluctuation in the number of ion pairs.

So you have a large number of atoms in the material and so you have what you follow is the Poisson distribution. The probability of interaction of the radiation in the particular atom is very small. So we follow the Poisson distribution whenever the probability is very small and the ensemble size is very large. For a Poisson distribution, the second moment, the variance is equal to the mean. So take the mean as the number of ion pairs that are produced N, then the variance is equal to mean and variance is square of the standard deviation. So σ will be root of mean. That means the fluctuation in the pulse height.

FWHM will not be σ, it will be actually 2.35σ for a Gaussian. The fluctuations in the pulse height are related to square root of the number of ion pairs. So if you want to have a better resolution, go for a high number of ion pairs or low W. So that consequences we will see subsequently. So for a Gaussian, the FWHM is given by 2.35σ. You can derive from the full width at half maximum how it relates to the standard deviation of a Gaussian. So energy resolution (R) will be 2.35σ FWHM/H_0. H_0 is proportional to number of ion pairs. So N and σ is $\sqrt{N}$. So you can convert this in terms of $\sqrt{N}/N$, $2.35\sqrt{N}/N$ where N is the number of ion pairs formed. And so you can now see that resolution, it depends upon is equal to $2.35/\sqrt{N}$. So higher the number of ion pairs, better the energy resolution. This is how the resolution, when we discuss different detectors, you will find that the resolutions are different because of the number of ion pairs that are produced.



Detection efficiency

Absolute efficiency (ε_a) = No of counts/No of quanta emitted by source

Intrinsic efficiency (ε_i) = No of counts/No of quanta incident on Detector

Geometric efficiency (ε_g) = $\Omega/4\pi = \pi r^2/(4\pi d^2) = r^2/4d^2$

$\varepsilon_a = \varepsilon_i \times \varepsilon_g$

Counts per second (CPS)

= Disintegrations per second (DPS) x ε_a

Another important property of detectors is the detection efficiency. How efficiently the detector can count your maximum radiations. So the radioactive sources, they will be emitting the radiation in all possible directions, in 4 pi. Though even if you put a collimator, then we are losing the radiation in other directions. So isotropic emission of radiation is the property of radioactive sources. They are emitting in all directions. But your detector has got a finite dimension.

So if suppose you have a cylindrical detector having a radius r at a distance d from the source. So there is something called the geometrical factor, what fraction of the radiation is falling on the detector, that is called the geometric efficiency. Out of that fraction, whatever is falling on detector, what fraction is being counted, that is called the intrinsic efficiency and the product of the two we will call as the absolute efficiency. So we will go in the reverse direction.

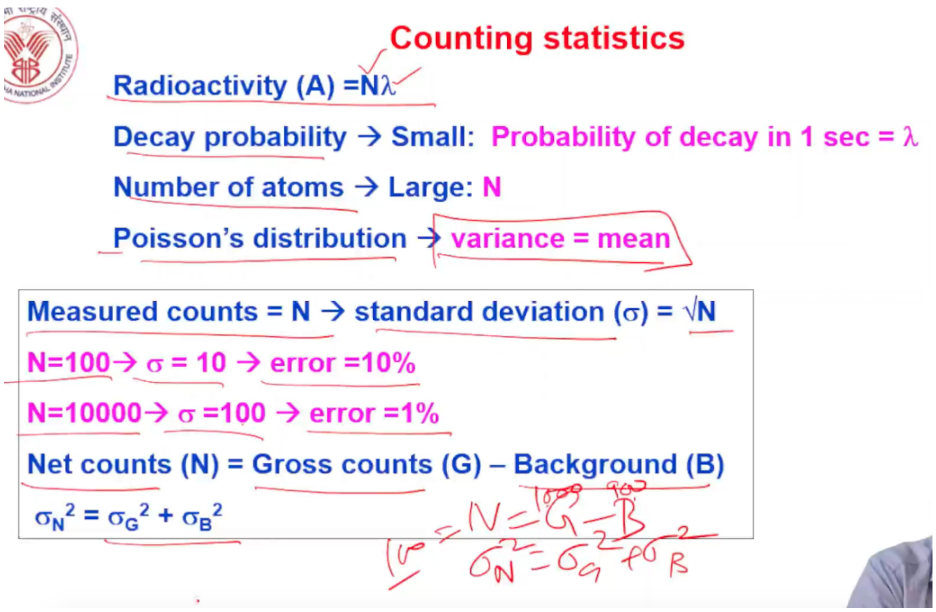
Geometric efficiency is the solid angle subtended by the detectors at the source ($\Omega/4\pi$). And this $\Omega/4\pi$ can be written in terms of the area of the detector surface into surface area of the sphere $4\pi d^2$. This detector can be considered as the part of this area of a sphere. So like you know, you can have a cirle on the surface, you have a small portion is covered by the detector. So $\pi r^2/4\pi d^2$ is the fractional area covered by the detector. So that is called the geometric efficiency. It becomes $r^2/4d^2$. So you can play with the geometric efficiency, have a large area detector, bring it close to the source and so on.

Then out of this fraction is in the detector, what fraction is counted that is called the intrinsic efficiency. Intricic efficiency, number of counts upon number of quanta incident on detector because every radiation that is falling on detector may not be counted. So there may be other processes or radiation may escape. So that is called the intrinsic efficiency.

The product of the intrinsic efficiency and geometric efficiency is called the absolute efficiency. So absolute efficiency equal to intrinsic efficiency into geometric efficiency. And so you can in fact call absolute efficiency as number of counts in the detector system upon number of quanta emitted by the source. So suppose it is emitting 100 counts per second, 100 radiations per second out of those 100, how many are counted by the detector that is called the absolute efficiency.

So in practice we will be using absolute efficiency. You can have a standard source and find out how many counts you are getting. But it is a product of two quantities, geometric efficiency and intrinsic efficiency. Geometric efficiency depends upon geometry of the detector system. Intricic efficiency depends on the detector material. Even it can depend upon the energy of the radiation. So when we count the activity, we say counts per second in the peak. Suppose you have a peak like this, take the counts. This is the energy versus count. So this area will be the counts where it is counted for a particular time divided by the time, we call the counts per second. And so but it is not necessary that all the disintegrations are being converted into counts.

So suppose it is emitting certain photons, so efficiency is taken care by the fraction actually counted. So the disintegration per second, that is, activity is a_0 into efficiency equal to x. So initial activity, this is the source activity and this is the counts. So you can, if you know the efficiency, if you know the counts, you can find out the absolute efficiency. a_0, absolute activity is a upon efficiency. So if you know the counts per second, you know efficiency, you can find out the disintegration per second. So this efficiency is a very important property of a detector.



Counting statistics

Radioactivity (A) =Nλ

Decay probability → Small: Probability of decay in 1 sec = λ

Number of atoms → Large: N

Poisson's distribution → variance = mean

Measured counts = N → standard deviation (σ) = √N

N=100→ σ = 10 → error =10%

N=10000→ σ =100 → error =1%

Net counts (N) = Gross counts (G) – Background (B)

$\sigma_N^2 = \sigma_G^2 + \sigma_B^2$

$100 = N = \overset{1000}{G} - \overset{900}{B}$

$\sigma_N^2 = \sigma_G^2 + \sigma_B^2$

Now comes the counting statistics. So when you are counting a source, you should know for how much time you should count because there is a limitation on the time also. So let us discuss this in more detail. So essentially the errors, the uncertainty in the numbers dictate for how much time you need to count. For radioactivity, we have already discussed activity equal to Nλ. How many atoms are decaying in one second, atoms per second, it is called number of atoms into the probability of decay in one second λ. So again, going by the probabilistic aspect of this number of atoms in a sample can be very, very large, could take a gram, it can be close to Avogadro number, and then the λ decay constant is a very small quantity. So whenever you have a very small probability of decay and very large sample size, the decay follows a Poisson's distribution. So counting of the radiation in a detector system will follow Poisson distribution for which the variance is equal to the mean. That means if you have a single count, you counted the sample and you get some number N, from that we can find out the uncertainty in the data.

So suppose you get N counts in a detector system. And so you have only one value, how do you find out the uncertainty? Use this formula.

σ= √N

So that is how you get the uncertainty in the counts. So just let us take an example that if suppose you get 100 counts in a detector system, then σ = 10. So uncertainty will be 10 by 100 into 100, 10%. But if you count for 10,000 counts, uncertainty σ = 100, the error on that will be 1%. 100/10,000 × 100, 1%. You can see that by accumulating more counts, you can decrease the uncertainty in your counts. So that is what dictates for how much time you should count a sample.

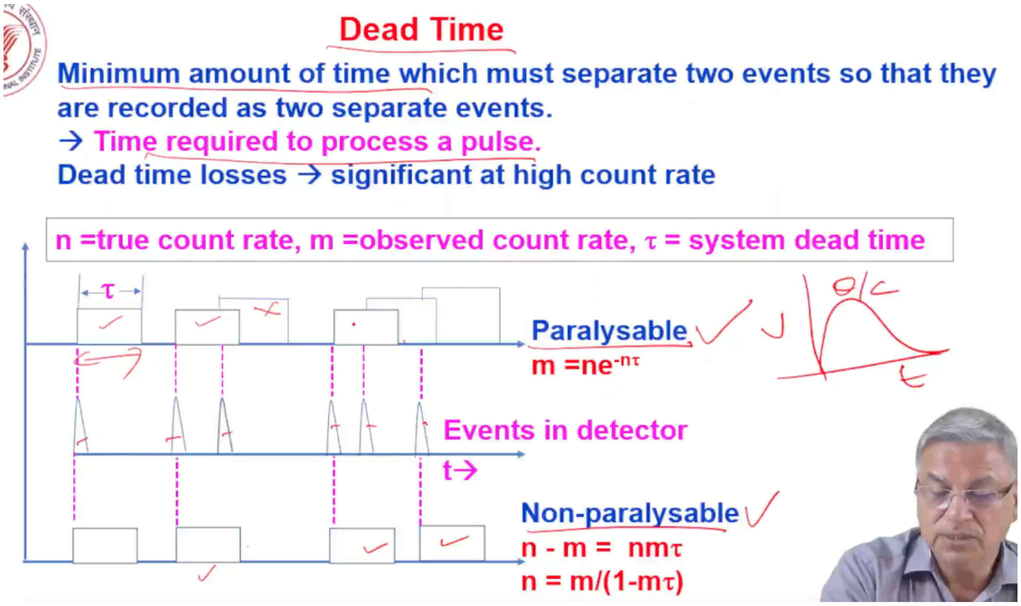
If you want 1% uncertainty, then you could count for 10,000. You accumulate 10,000 counts. So your time, counting time is governed by what is the uncertainty that you want to achieve. So many times you know you have sample will have your detector system will have a background also. So when you are counting a sample, it will also have background. So you have to subtract the background. Without the sample you count, you get background. So the net count will be gross count minus the background. So you put the sample, you get a count, you remove the sample and you just count without sample or background. So net counts equal to gross count minus background. And so correspondingly the uncertainty is

$\sigma_N^2 = \sigma_G^2 + \sigma_B^2$

So they have their own uncertainties. So the errors are additive. Though you are subtracting gross count minus background, the errors are additive. So if gross count is let us say 1000 and background is 900. Net counts is equal to 100. But error will be $\sqrt{(1000 + 900)}$.

$N=1000-900=100$, $\sigma_N = \sqrt{(1000+900)}$

This is the sigma. So if the background is high, the error on the numbers is very high. So you have to reduce the background, you get more reliable results. These are the things one has to take care of in counting.



Dead Time

Minimum amount of time which must separate two events so that they are recorded as two separate events.

→ Time required to process a pulse.

Dead time losses → significant at high count rate

n =true count rate, m =observed count rate, τ = system dead time

Paralysable

$m = ne^{-n\tau}$

Events in detector

t→

Non-paralysable

$n - m = nm\tau$

$n = m/(1-m\tau)$

And the last thing property of detectors is the dead time. Dead time is when a detector is processing a particular event. During that time, it cannot process another pulse. So during that time, while it is processing one pulse, it is said it is dead to receive another pulse. So essentially the dead time is the minimum amount of time which must separate two events so that they are recorded as two separate events. So essentially the dead time is the time required to process a pulse. During that pulse, if another pulse comes that may not be or may be counted. It depends upon what type of system you have. And this happens when the system has got high count rate, then there will be some pulses will be lost. So the dead time losses are important.

So that tells you what should be the sample activity. Suppose you put a one milli-curie sample, means 3.7x10^7 disintegrations per second, then there will be one count for every 0.027 microsecond., which you cannot count. So you require very small quantity, a micro-curie or less. So I will just try to explain, there are two models of dead time, parallelizable and non-parallelizable.

That means, see there is a train of events, these are the pulses coming in the detector system. And for each pulse, you require certain time to count, process the pulse. So if you recall the time versus voltage, Q/C. So this is a voltage signal, I am showing a logic signal, square pulse. Now I have shown six events are coming in the detector spaced by the time in different manner.

So here this pulse is counted. This pulse, before this pulse is over, another pulse has come. And here two pulses have come. So one after one more, three pulses have come. Depending upon whether it is parallelizable mode or non-paralysable, you will get different events in the detector system. In the non-paralysable mode, in the second pulse, when this is coming, the second pulse is not counted

You see here, whereas this here, there are three events, they are counted as two events. Because after this, the detector is available to detect the other pulse. Whereas in the paralysable mode you get one event here.

This is again one event. And this whole thing is coming as one event. Because it is paralysed. So this detector is seeing this whole thing as one event. So you get three events, you get four events. Actually there were six events. So that is the difference in meaning of the paralysable and non-paralysable mode of dead time.

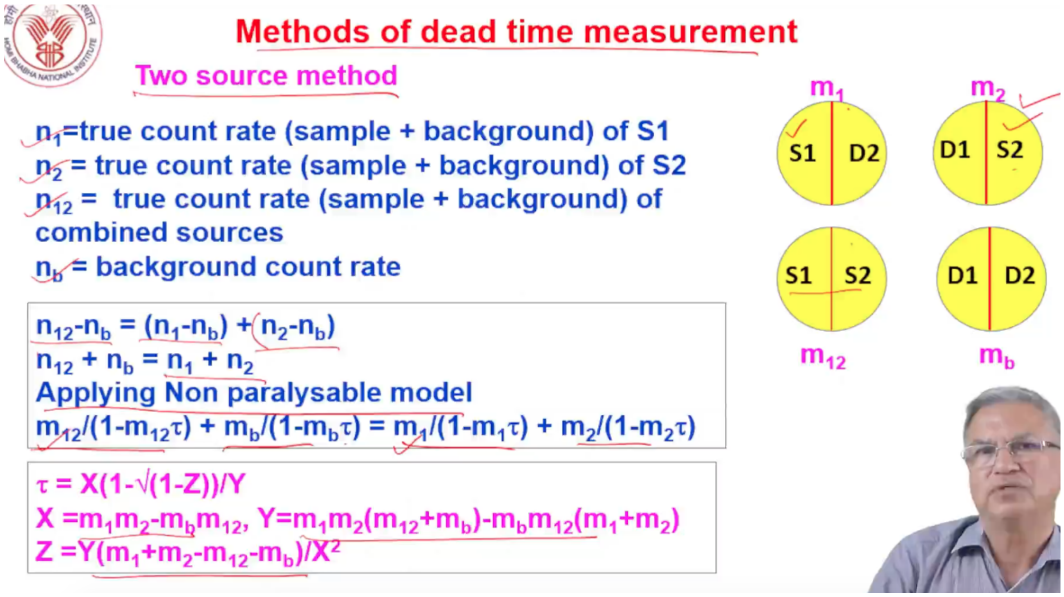
And depending upon the type of model for dead time, there are the observed count rate. So if n is the true count rate. How many quanta the sample is emitting. How many observed, m is observed count rate and τ is the dead time, so the relationship between the observed count rate and the true count rate for paralysable mode are

$m = n\ e^{-nr}$

And for non-paralysable mode it is

$n = m/(1-m\tau)$

So the detector system will follow either paralysable or non-paralysable mode. One has to do an experiment to see what kind of model the detector follows.



Methods of dead time measurement

Two source method

n_1=true count rate (sample + background) of S1
n_2 = true count rate (sample + background) of S2
n_{12} = true count rate (sample + background) of combined sources
n_b = background count rate

$n_{12}-n_b = (n_1-n_b) + (n_2-n_b)$
$n_{12} + n_b = n_1 + n_2$
Applying Non paralysable model
$m_{12}/(1-m_{12}\tau) + m_b/(1-m_b\tau) = m_1/(1-m_1\tau) + m_2/(1-m_2\tau)$

$\tau = X(1-\sqrt{(1-Z)})/Y$
$X = m_1m_2-m_bm_{12}$, $Y=m_1m_2(m_{12}+m_b)-m_bm_{12}(m_1+m_2)$
$Z = Y(m_1+m_2-m_{12}-m_b)/X^2$

So just to see how this one can determine the dead time of a detector system. So for this purpose, people follow two source method. Two sources, let us say their activity is S1 and S2. So you count S1 separately, you count S2 separately and then you count S1, S2 together. So when you count S1, S2 together, there will be losses in the counts because the count rate has increased. And so this can be made use of in finding out dead time. And this D1, D2 are the dummy. Dummy means when you are not putting any sample, you put a dummy source. There is no activity in that, that is what dummy source.

So you have now four sources, S1, S2, D1 and D2. D1, D2 are the dummy. These are D sources, the dimensions are of a semicircle. And so you can put, so n1 is a true count rate for sample one, source one. n2, true count for source two. And when you put them together and count, you get the n12 as true count rate of the combined source. And there is a true background count rate. But actually what you get is not n, you get m. So we can try to analyze $n_{12}-n_b$, the background, you subtract the background, $(n_1-n_b) + (n_2 - n_b)$. The true counts, so you can arrange

$n_{12} + n_b = n_1 + n_2$.

This is not the count, what you are counting, what you have the true activity counts of the sample. Now you apply the non-paralysable model,

$m_{12}/(1-m_{12}\tau) + m_b/(1-m_b\tau) = m_1/(1-m_1\tau) + m_2/(1-m_2\tau)$

So this is an equation where you are observing the counts. m1 is when you have put S1, m2 is when you put the S2, and m12 is when you put both of them together.

And D1, D2 when you put background, they are called m_B. So from this you can solve this equation to find out the τ. The τ comes in terms of X, Y, Z,

$\tau = X(1-\sqrt{(1-Z)})/Y$

$X = m_1m_2-m_bm_{12}$

$Y = m_1m_2\ (m_{12}+m_b)-m_bm_{12}(m_1+m_2)$

$Z = Y(m_1+m_2-m_{12}-m_b)X^2$

They all depend upon the $m_{1,}$ m_2, m_b and m_{12}. So you can actually just calculate the dead time by the non-paralysable model. Particularly if there is an experiment for the GM count, and if you happen to use a GM counter, one can use this two source method to find out the dead time of a GM counter. This is a very simple experiment for the radiochemistry people to determine the dead time of a GM counter. That comes to about a few hundred microseconds.

So today what I tried to show you the different properties of the detector systems. And these properties will be used when discuss the different detectors, then we will use the terms quite often in our discussion. So I'll stop here and next time we'll discuss the different type of detectors. Thank you very much. Thank you.