Gas filled detectors

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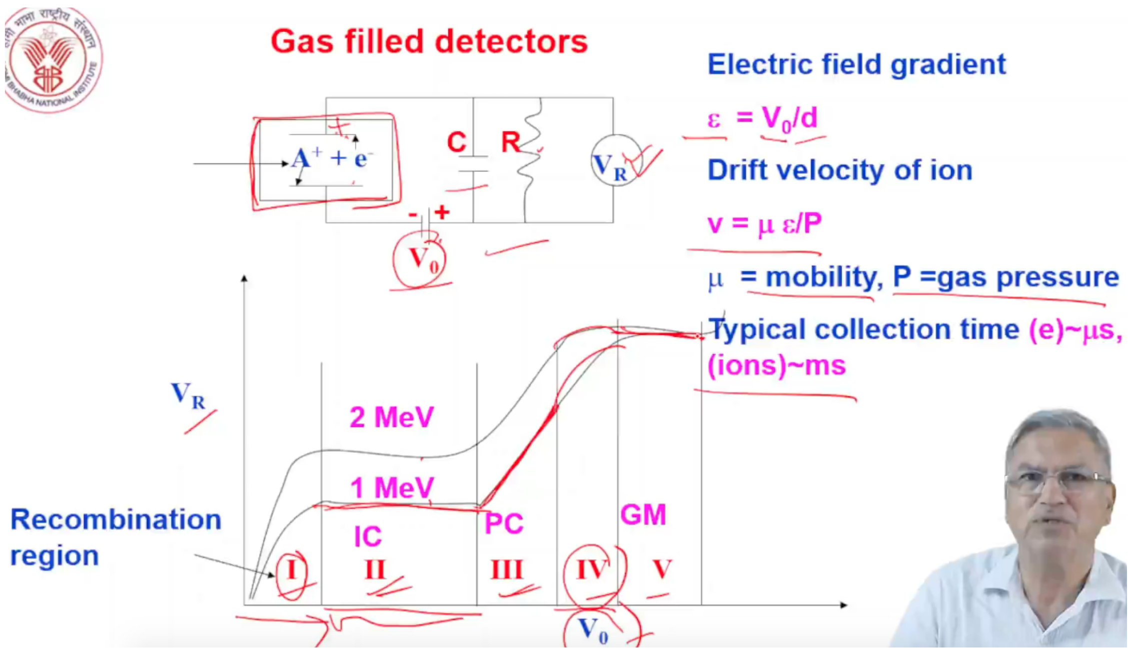
Lecture-9, module-2

Hello everyone, welcome to this lecture on radiation detectors. In the last lecture I discussed the basic principles of radiation detectors and certain properties of detectors like energy resolution, detection efficiency, dead time etc. Today we will discuss the basic principles of gas filled detectors and what are their applications.



The gas filled detectors the basic principle is schematically explained using this diagram here where we have a rectangular geometry of the gas filled counter it could be a tube it could be a rectangular box which contains two electrodes namely cathode and anode. And you have to have a let us say some window through which the radiation can enter the chamber. Once the radiation enters the chamber already you know that whether it is alpha or beta or gamma, it will cause ionization and excitation and the detector functioning depends upon collecting these ion pairs it could be positive ion, electron, in some cases electron-holes and so on.

So the idea lies in collecting the electrons at anode. So you apply a bias at the anode here you apply a potential through this battery. Electrons go towards the anode and then when the charge is collected at the capacitor this capacitor will discharge through the resistance and you can put a voltmeter to see the voltage signal at this particular place. So essentially it is the mobility of ions, particularly the electrons in electrical field gradient that dictates the performance of a detector. So when the electrons are moving across the electric field gradient that gradient is given by

$$\varepsilon = \frac{V_0}{d}$$

so it is like a parallel plate chamber. So between two plates, there is a linear gradient in the electric field so if V_0 is the potential applied at the anode and d is the distance between the cathode and anode, then the electric field gradient will be given by $\frac{V_0}{d}$ and then the how fast the electrons will drift towards the anode depends upon the drift velocity, which is given by

$$v = \mu\varepsilon/P$$

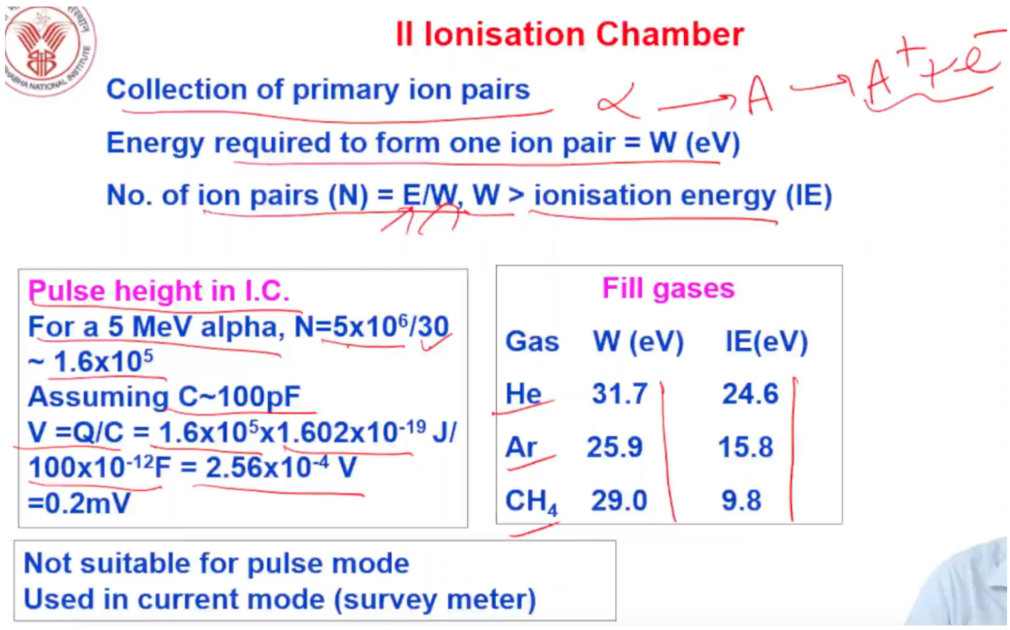
where μ is the mobility of the electron, P is the gas pressure and ε is the electric field gradient. So the typically you know the electron will take about microseconds to reach the anode, it can reach much faster but you know later on we will see there is an avalanche of electrons produced in different types of detectors so that may make the process little sluggish. Whereas the positive ions being bulkier take hundreds of microseconds to even milliseconds to reach the cathode. So the principle of the detector system for a gas filled counter displayed by this figure here where we have different zones of applied voltage V_0 at this place and the voltage signal at the voltmeter. The relationship between these two quantities the voltage signal at the voltmeter and applied voltage dictate the functioning of different types of detectors.

So to begin with when you have very low applied voltage, let us say we are in the region 1 then this electric field gradient is not sufficiently high that the electrons will be able to reach the anode and positive ions will reach the cathode before that they can recombine and that is why as you increase the applied voltage more and more electrons and positive ions are reaching the electrodes but even then all the primary electrons and holes are not collected and so this is called the recombination region means where the electrons and positive ions combine to form neutral atoms. So it is not useful for the detector.

Then come to the second region ionization chamber IC means ionization chamber and in fact these two graphs are for two radiations of different energy so higher the energy of radiation higher will be the pulse height that you get in the detector. So in the second region, ionization chamber the primary ion pairs that are produced as a result of interaction of radiation with the gas material all the primary ion pairs are collected. And so that is why you see the pulse height remains constant over this region of applied voltage. This is called the ionization chamber whereby we collect the ion pairs across the electrodes and it is a constant voltage because whatever what ever ion pairs are collected generally all are collected.

Then comes the third region, the PC the proportional counter where there is secondary multiplication that means whatever primary ion pairs are produced in the gas medium they are further multiplied because the electron will acquire energy because of the higher electric field you are applying a higher potential and so the primary electrons can further cause ionization leading to secondary ionization and there is a multiplication in the number of ion pairs. But that multiplication factor is constant. Therefore, the number of charge carriers is increasing proportionately to the initial energy of the radiation. That's why it is called the proportional counter.

When you further increase the applied potential to this region then there is a sort of saturation type of occurring and this is called the region of limited proportionality and again this region is not useful for detector application. But finally a situation comes where irrespective of the energy of radiation like I MeV, 2MeV or any other type of energy radiation you will find that you get the same pulse height in the detector that is called the GM region, Geiger Muller region. We will explain the details of the detectors subsequently. So Geiger Muller gives you the same pulse height irrespective of the type of radiation or its energy.



Now let's come to the first detector type that is the ionization chamber. I already explained briefly about this that the ionization chamber depends upon the collection of primary and pairs. That means let us say the $\alpha \rightarrow A \rightarrow A^+ + e^-$, so this is the primary ion here and collection of this primary ion pairs across the anode and cathode respectively will give rise to a voltage signal at the voltmeter.

So let us see how many ion pairs can be produced by interaction of particular energy ion so that will depend upon the W value. W value is the energy required to produce an ion pair which should be in fact in principle should be equal to the ionization energy but now we know that all the interactions do not lead to ionization. Some of them may lead to even excitation. And therefore the W value is higher than the ionization energy of the particular gas medium. So the number of ions that are produced is energy of radiation upon the W value.

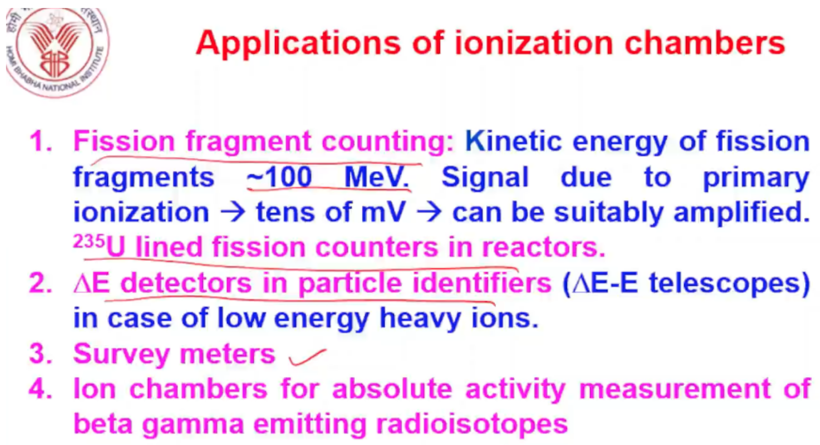
No. of ions produced (N) = E/W

The typical W values are given for different filled gases like Helium, argon, methane you can see here the ionization energies are in the range of tens of electron volt and the W values are higher than the ionization energy. Because some of the interactions may not lead to ionization they may lead to excitation.

Now Let us have an idea about the what is the type of pulse height that you get in the detector in an ionization chamber. So the pulse height in an ionization chamber can be calculated from that circuit diagram which we showed you. It has a capacitor and it capacitance will discharge through a load resistance. So let us see you have a 5 MeV alpha particle. So what is the W value? W value let us take 30 electron volt so W is 30 eV and there are 5×10^6 electron volt energy of radiation. So

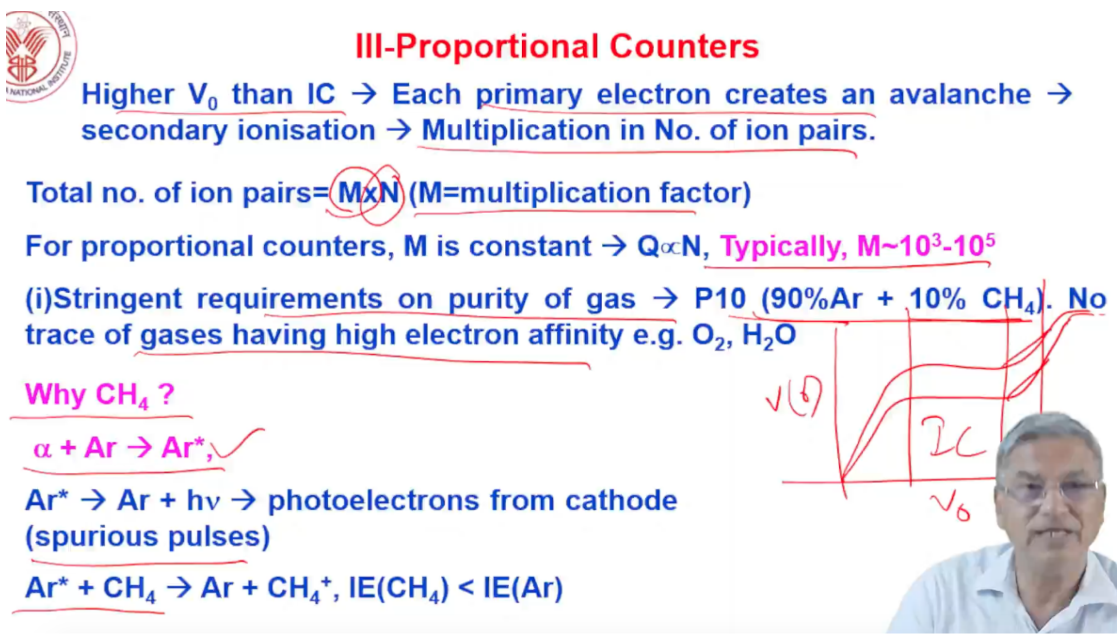
$N = 5\times 10^6 /30 = 1.6 \times 10^5$

This energy 1.6×10^5 ion pairs. Now just take typical capacitance of the detector system as 100 pico farads. So the voltage signal at the voltmeter will be Q/C where Q the charge C is the capacitance. So you can put the charge due to this many electrons multiplied by the charge of one electron that is 1.602×10^{-19} coulombs and then they are divided by the capacitance 100 Pico Farad so that becomes 2.56×10^{-4} volts or of the order of 0.2 millivolt you can see here that. The signal is quite weak for a 5 MeV α. Because of that these detectors are not really suitable in pulse mode. Instead of that if you have a constant source of radiation you can use it in current mode. That is what happens in a survey meter. In a survey meter you just keep on detecting the radiation level in a current mode. It tells you the level of radiation. So ionization chambers are actually used in survey meter which give more qualitative idea than the quantification of the radiation levels.



So the applications of ionization chambers lie in fact there are some cases like fission fragments. Fission fragments have very high energy of the 100 MeV and because of that when the primary ion pairs you will get so compared to 5 MeV, it is 20 times more so 20 × 0.2. You can see here 20 × 0.2. So almost 4 mV. So 4 mV is a good signal so particularly fission fragments can be counted in ionization chamber without any background and in fact in reactors, ^{235}U line chambers are used for neutron monitoring in reactors. In addition to that they are also used in ΔE-E detectors in particle identifiers in nuclear reactions where the heavy ions you want to detect them by using a ΔE-E telescope.

But mostly the survey meters in current mode ionization chambers are used and in some applications like ionization chambers where you have a big source of curies or few milli curies. Then you can determine the absolute activity using a 4 Pi counter where all the radiation that is emitted/deposited in the chamber. And you measure the current. So ion chambers are also used for measurement of activity of intense sources. These are the applications of ionization chambers but when it comes to the routine counting in pulse mode, we don't use them. We use other chambers called proportional counters.

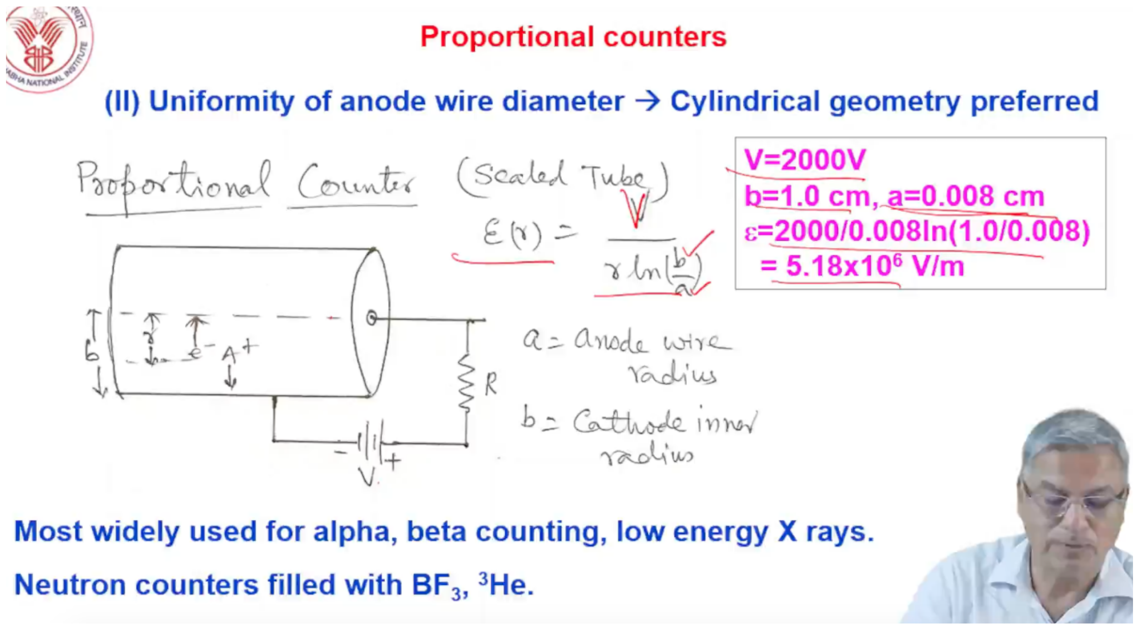


In proportional counters if you recall the curve V_0 versus the voltage signal then this is the one. So you have this ionization chamber region IC, and then we have a proportional region where there is a secondary multiplication. So at higher voltage, than the ionization chamber, this primary ion pairs can further undergo ionization in the gas medium and so each primary electron that is produced it will cause an avalanche of ionization and then so there will be a larger multiplication. For this multiplication of ion pairs is the inherent property of proportional counters and the important point is that the multiplication factor is constant.

Suppose you have got N ion pairs produced as a result of primary ionization, then the total charge that is produced is M×N where M is the multiplication factor. So the main point of this counters is that M is constant and that puts a strict requirement on the parameters of this proportional counter. And the typical multiplication factor is 10^3 to 10^5. So you can see the pulse amplitude will increase by this much magnitude but then the fact that M has to be constant put the requirement on the purity of the gas. So there should not be any gas medium which will have a high electron attachment coefficient means any electronegative gas like oxygen or moisture they can pick up electrons from the ionization and so they can change their multiplication factor.

So typically argon gas, 90% argon and 10% methane, that is called P10 gas without any traces of a gas having high electron affinity like oxygen or moisture. So this P10 gas is commercially available and they are filled in the proportional counter tubes. So the question arises why this methane is used in this proportional counters along with Argon. The reason lies in that when you have argon if you take pure argon, then the charged particle can cause ionization and sometimes it can also cause excitation. So these excited argon atoms can emit photons; ultraviolet or visible photons, and these photons can cause emission of photoelectrons from the cathode. So once this photon is escaping out of detector's volume upon reaching the cathode by photoelectric effect, it can generate a photoelectron and that photoelectron is actually not wanted. So this causes spurious pulses. So to take care of this spurious pulses that they don't arise we use a polyatomic gas which will collide with the excited argon atoms and the argon comes to neutral ground state whereas the methane gets ionized. So we have some excited argon atoms, we have got some ionized methane molecule and therefore methane serves to quench the produces spurious pulses.

$Ar+ + CH_4 \rightarrow Ar + CH_4^+$



So proportional counters in fact come in different modes like the sealed proportional counters. So this you have a cylindrical tube where you can fill the gas and the anode wire has to be very thin. micron size, very thin you can see here typical diameters of let us say to 0.008 cm or 0.08 millimeter so almost 80 microns. So this thin anode wires are the hallmark of proportional counters because they have to be uniform in thickness. So the uniformity is same that means the electric field gradient is constant all along the length of the anode wire. Then proportional counters if you use them in the cylindrical geometry then you can have very high electric field gradients which at any distance r from the anode wire is given bhy

$V(r) = V_0/r \ln(b/a)$

where b is the radius of the proportional counter and a is the radius of the anode wire. So you can see here that by applying a small voltage you can have very high electric field gradient. So r ln(b/a) just to give you a field if you apply 2000 V as the potential at this battery, and b the radius of the tube is 1 cm, the anode diameter is 0.08 cm then you can see by this formula we have at the anode wire 5 MV/m is the electric field gradient which is much higher than that you get in the ionization chamber.

So because of that you can achieve the secondary multiplication and then you will have the high pulse height. In fact, gas filled proportional counters have a problem of you have to have very high purity of the gas there should not be any moisture or oxygen and because of that there are a variety of variant of proportional counters called flow proportional counters.

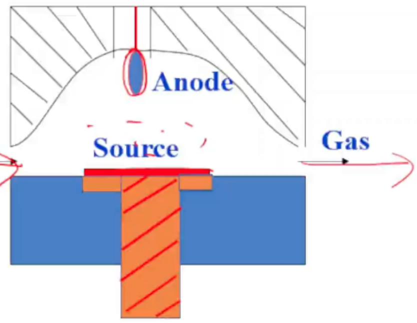
Flow proportional counter

Detection efficiency ~50%.

Energy resolution ~0.5%

For 5 MeV alpha, $N=5\times10^6/30 = 1.6\times10^5$

$R = (2.35/\sqrt{N}\times100 \sim 0.6\%$



Advantages:

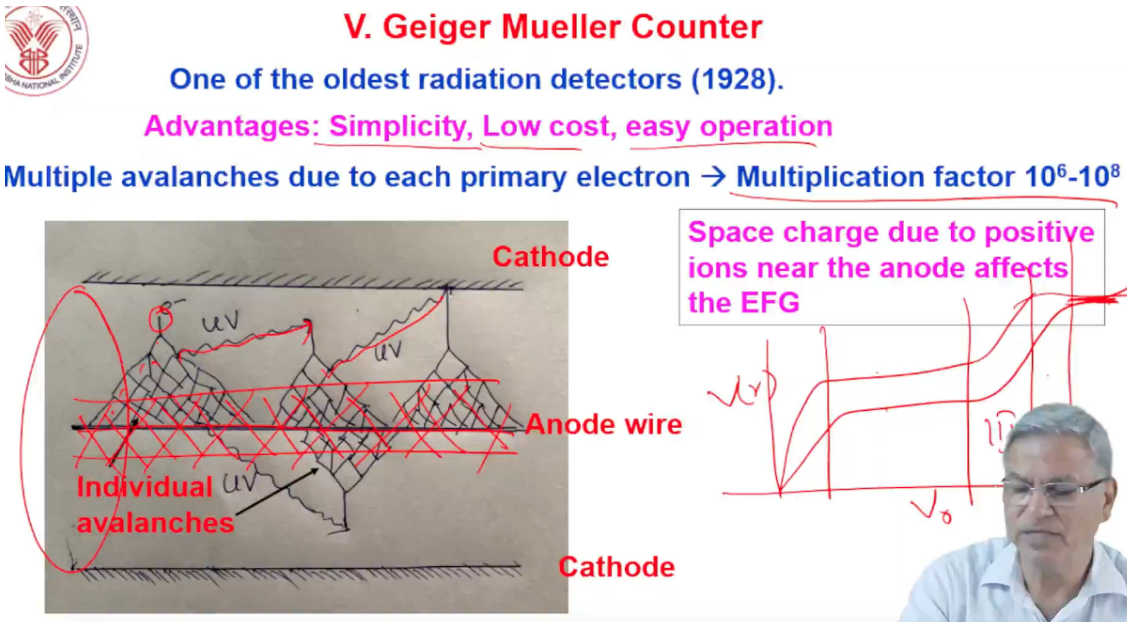
1. High detection efficiency
2. No window → no attenuation
3. Possibility to change the fill gas
4. The circulating gas can be purified

The flow proportional counters what happens it is not a shielded tube but you have an assembly where you can allow the gas to flow from one side and it's coming out from the other side. You keep the source in the center of the base plate. The base plate can be lowered down so that the source can be inside the cavity or if you want to raise when you have to count you raise it up in the platform. And in fact this can remove it from this side by using a plate system so you can lower it and then take it out. Then you have the anode in the form of a loop on which you have to apply the positive potential. So the flow of the gas has got the advantage that the purity need not be so strictly high. You can purify the gas you can have it in the circuit you can have a circulation loop for purification. The advantages are many. One is that now the there is no window. So just the like alpha particle there is no loss of energy of alpha in the window. There is no window. Source is exposed to the gas medium. Second is that the geometry is 2π. So you have almost 50% efficiency for counting. So very high efficiency. Resolution is 0.5%. We can see for a 5 MeV alpha and 30 electron volt is the W value. You get 1.6× 105 amperes. Resolution will be 0.6%. So you have high resolution, high detection efficiency and the purity of the gas is not that strict now because you can purify the gas as it is circulating. So no window. These are the advantages. Now many places, the radiological laboratories have the flow proportional counters available in their counting systems.

Proportional counter applications

1. Xe or Kr filled proportional counters for XRD: High Z gases →high photo-fraction for X-rays.
2. ^3He or BF_3 gas filled neutron counters: Neutron well coincidence counter (NWCC)
3. Gas flow proportional counters for alpha counting, beta counting as well as fission fragment counting.

The proportion counters have applications like you know if you are using the dispersive X-ray diffraction system, then for x-ray counting you can have proportional counters filled with high Z gases like Xenon, Krypton. With high Z gases will have high photo fraction. For neutron counting you can have ^3He to BF_3 gas filled counters and other than that you have the gas flow proportional counters for Alpha counting, β counting. Even you can use the fission fragment counting in this proportional counters. So there are a lot of applications of proportional counters so can use any gross counting of α, β, or low energy x-rays.



Lastly I come to the Geiger Muller counter. Geiger Muller, GM counter we commonly called. In fact, they are one of the oldest detectors. They were developed by Geiger and Muller in 1920s and despite that you know after almost now is going to be a century they are still being utilized widely in laboratory experiments because of the simplicity, low cost, ease of operation, very easy to operate.

I'll show you a photograph of the detector system. So the GM counters still are in the experimental laboratory when you are doing experiments for the MSc students or you know any PhD students initial training. In fact, some of the applications where simple counts are required GM counters can be used. So if you recall again the graph V_0 applied potential versus the signal and we showed that for two detectors. So this was the recombination region. This was the ionization chamber, proportional region and here is the limited proportionality. And now here, at still higher applied voltage, you will find both the radiations have given the same pulse. In fact, not only these two radiations you take any photon, even one electron, one Photon of any energy, will give you the same pulse height. So that is the specialty of the GM counter.

But this also has the drawback that it does not distinguish between different types of radiations. So I'll try to explain this GM region in more details here. What I have shown here in this graph is called the Cascade of avalanches. In proportional counter what happened. Every primary ion pair every electron that is produced in primary ionization each electron produces one avalanche. So what I have shown here is the avalanche. Avalanche means each electron is multiplied several times when it is undergoing ionization in the medium. So per electron in proportional counter gives you thousand to ten thousand counts. When avalanche size is 10^3 to 10^5.

Whereas in the case of Geiger Muller counter, each electron that is producing an avalanche and every avalanche can produce other multiple avalanches. So it is a continuous process of avalanches generated by not only the primary electrons but also by the secondary electrons. Because of that these GM counters have very high multiplication factors of the order of 10^6 to 10^8 times signal is multiplied.

So what is happening is that when the electron is generated at any point let us say it is produced here. So this is a tube you can see here this is a tube this is the anode wire and now wherever the electron is produced it will try to go to the anode and along the path of the is going towards anode it will be generating ionization. That ionization and during that ionization process it can even cause that there will be excited molecules which will emit light. So UV radiation will be emitted. These UV photons can further cause ionization and generate another avalanche. Again from this you can have another UV Photon generated avalanches and it can be from the other side also. It is like an anode wire is you know it is in the tube so you have all along the across along the surrounding the anode wire you have the gas. So on all sides of the anode wire there will be sequence of avalanches and this avalanches can be generated by electrons or the UV radiations that are produced in the de-excitation of the excited molecules.

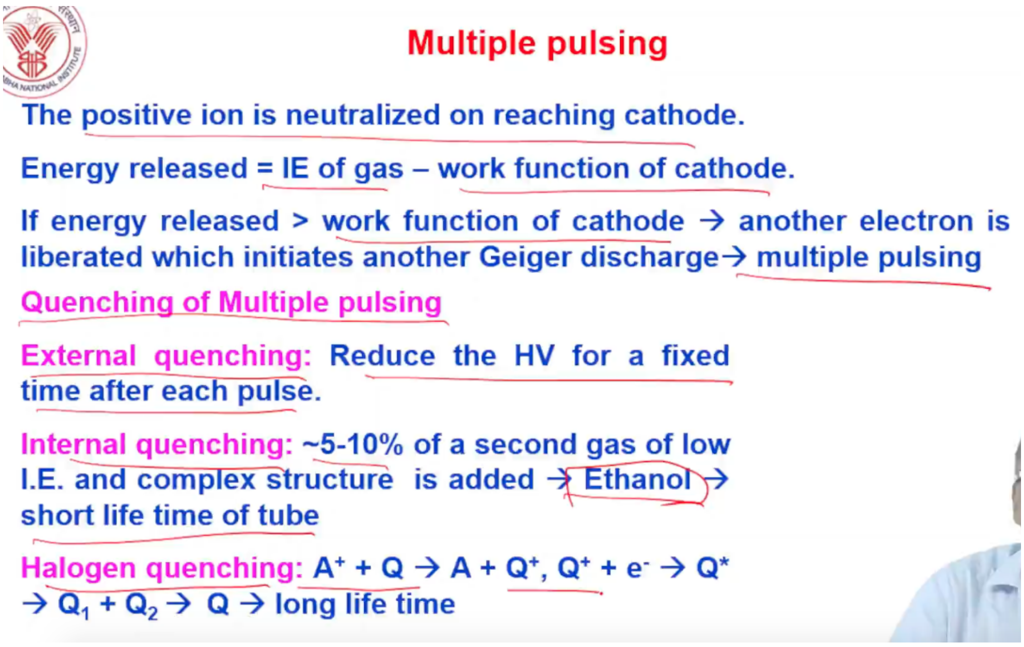
So this avalanches generate a large number of electrons and pairs. So ultimately what is happening is that the so many electrons are collected within a few micro seconds but at the same time there will be a sheet of positive ions. These positive ions are going towards the cathode. But their velocities are much low. So what happens because of the slow movement of the positive ions along the anode wire there will be a sheath as a cloud of positive ions. That's so much space charge due to positive ions around the anode. In fact, that space charge becomes so high because that is now dictating the performance of the detector.

So what happens that when the space charge becomes very high the effective potential across the anode becomes low and then the detector stops functioning. Because you require a certain applied. But because of the positive space charge generated due to several avalanches effective electrical gradient becomes low. And this happens only when a particular amount of space charge is created. So the process of avalanches continues till the space charge becomes so dominant that the detector stops functioning. So every time the space charge reaches certain value then the detector stops functioning. Because of that the Geiger Muller counter will stop functioning only when so much of space charge is created. So this in fact essentially explains why the Geiger Muller counter cannot distinguish between different types of radiation because till that time the space charge is being created you are going on creating the avalanches.

Geiger Muller Counter

1. Irrespective of the type and energy of radiation, GM tube gives the same pulse height.
2. It can not distinguish between different types of radiation.
3. Pulse height is high (~ few Volts)→ no amplifier needed.
4. Fill gases: Highly pure He or Ar, free of any traces of gases which form negative ions (e.g. O_2)

So that explains the simple functioning of the Geiger Muller counter. So irrespective of the type of energy and type of radiation the Geiger Muller counter gives the same pulse height. Further it cannot distinguish between different types of radiations whether it is a single electron or if it is an X-ray or alpha or beta or even fission fragment. All of them will give you the same pulse height. But the pulse height is very high which is few volts. You can imagine 0.2 millivolt was the pulse height in ionization chamber and now you have a very high multiplication almost a million times so you will have a few volts' signal. So you don't need even an amplifier. And that is why it becomes very rugged. Of course it has the restriction on the fill gas. Helium or argon pure highly pure helium or argon gases are needed. They should be free of any traces of gases which can form negative ion. So moisture and oxygen again are prohibited from the fill gases. Why this strict requirement of this purity of the gases what happens that there is some process called multiple pulsing.



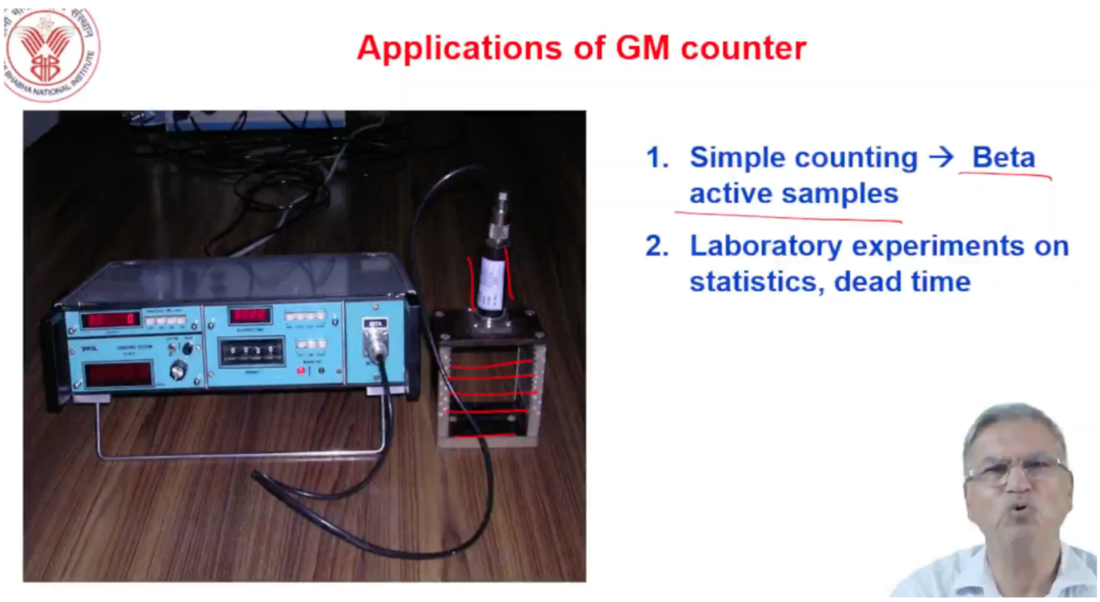
So what happens that we just now discussed that the positive ions are very sluggish to move towards the cathode. So there is a cloud of positive ions along the anode wire. But eventually even if it is few hundreds of micro seconds they will reach the cathode. And once they reach the cathode the positive ions get neutralized. During this process the energy is released, equivalent to the ionization energy of the fill gas molecule/atom. That much energy is released. So if this energy released happens to be more than the work function of cathode then what happens it can generate an electron from the cathode. So if the energy released during the neutralization of the positive ion is more than the work function of cathode, then another electron will be generated at the cathode and then that electron which is not wanted so that electron can generate another Geiger discharge and that is called multiple pulsing. So we do not want that the positive ion when it reached the cathode generates another electron so that is called the multiple pulsing which is not wanted in the Geiger Muller count.

So the multiple pulsing has to be quenched and that is done by different methods one is the external quenching.

Electronically that means where you can reduce the high voltage temporarily for a few hundred microseconds. So reduce the high voltage for a fixed time after every pulse you can have electronic system. But you know it affects the count rate. You cannot handle very high count rate. So normally it's not a very preferred mode.

Other methods are internal quenching. We use a five to ten percent of a second polyatomic gas of low ionization energy and having a complex structure so like for example ethanol vapors. So what happens now when the positive ions can collide with this polyatomic gas and this polyatomic gas molecule get dissociated. So instead of that positive ion reaching the cathode and generating another electron for multiple pulsing, they can collide with these molecules and lead to ionization. Or it can even get dissociated. But then then eventually what happens that these polyatomic gases will get exhausted because they will get dissociated and because of that the lifetime of this GM tubes are short.

Another method is halogen quenching where you have a chlorine or bromine gas which also get dissociated. So when the positive ion collides with this chlorine molecule Cl_2 you have the chlorine atoms produced. But these chlorine atoms can again subsequently combine to form the chlorine gas. Because of that they have a long life time. Halogen quenched GM tubes are very commonly available in market.



Lastly the applications of GM counter as I mentioned you cannot distinguish between different radiations and different energy also. So they are used for simple counting like if you have a simple beta active sample you can count the activity or in a laboratory you want to do experiments on statistics, dead time determination of a GM counter. So this is simple. This is the GM tube and you can put the samples in different geometry depending upon that these are the slots where you can put the sample and you can see there is no amplifier straight away you take the signal to the counting unit. You can apply the voltage and this is a very low cost instrumentation. Maybe about 50000 rupees you can even now get a GM counter so this instrument is very commonly used in the laboratory for demonstrating experiments on statistics, dead time. And if it's a pure beta source you can even count the activity. So I'll stop here. I'll take up the other detectors later. Thank you.