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Programme: M.Sc., Medical Physics

Course Title : Radiation Detectors and Instrumentation
Course Code : MP203

Unit-I

Principles of Radiation Detection and Gas Filled Detectors

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Definition (detectors):

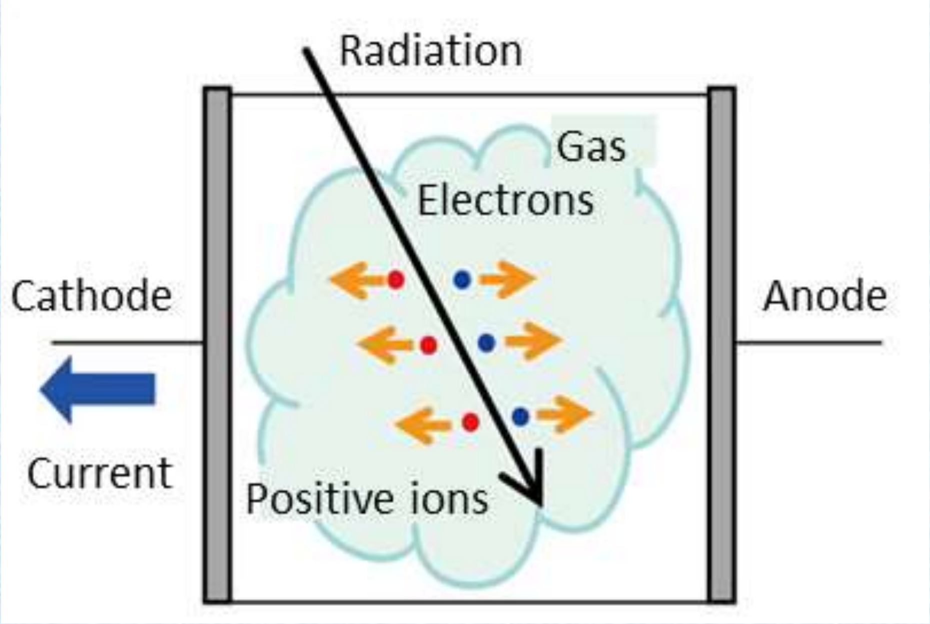
- **Detectors help to observe and detect or sometimes help to specify some specialties of particles taking part in introductions in atomic physics.**
- **These particles are generating during nuclear processes.**

Physical background of detection:

- **Particle (or its radiation) interacts with the material of the detector (In most cases the type of the interaction is electromagnetic).**
- Neutral particles cannot be detected directly.
- Neutral particles can be detected by charged particles generated by neutral particles. (Secondary particles.)

Principles of radiation detection and measurement:

- When **radiation** passes inside a **detector**, it causes ionization of gas atoms, separating atoms into positive ions and electrons.
- Separated electrons and positive ions are attracted to the electrodes, causing a current to flow.
- This is converted into electric signals, which are then **measured** as the amount of **radiation**.



General Aspects

- **Radiation detectors convert radiation energy into electrical energy.**
- **The electrical signal of a detector when irradiated is measured by an electrometer connected to the detector.**
- **By applying a certain detector specific calibration factor (e.g. Gy/C), the detector signal is related to a radiation dose value.**
- Detection system is pulse-type output
  – records a series of individual signals (pulses) separated or "resolved" over time
  – each pulse represents a separate radiation event within the detector

Pulse analysis can involve: Counting the pulses, Pulse height analysis and Pulse shape (duration) analysis.

1. Counting the pulses

The count or count rate can be related to the:

- ✓ exposure rate (e.g., mR/hr)
- ✓ dose rate (e.g., mrad/hr, mGy/hr)
- ✓ dose equivalent rate (e.g., mrem/hr, mSv/hr)
- ✓ activity of a source (e.g., dpm, Bq)

The device used to count the pulses is either a:

- ✓ rate meter or scaler

2. Pulse height analysis

- ✓ If the detector pulse height is related to the amount of energy deposited in the detector by the radiation, pulse height analysis (PHA) can be used to determine the energy radiation.
- ✓ Since the energy of radiation is characteristic of the radionuclide that produced it, pulse height analysis can be used to identify the radionuclide(s).
- ✓ The process by which we measure the energy of radiation is called spectroscopy.
- ✓ The number of pulses displayed as a function of pulse height (or energy) is a spectrum.
- ✓ A very simple form of pulse height analysis might be used to identify the type of radiation responsible for a pulse.

3. Pulse shape analysis

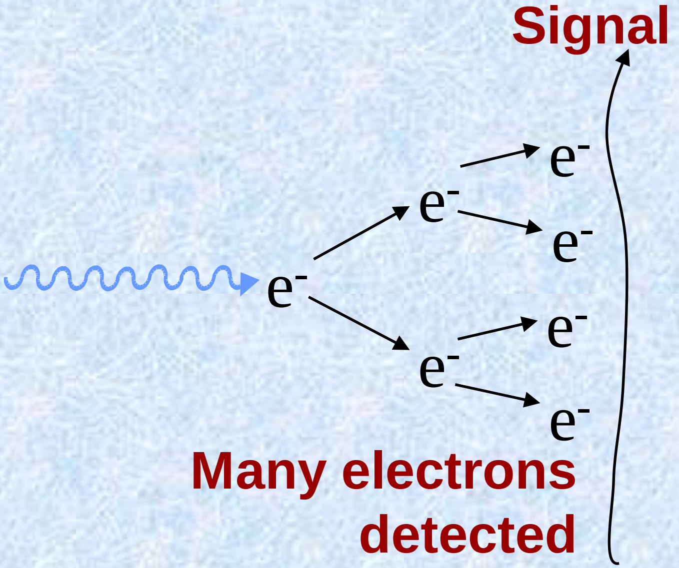
- ➢ Pulses produced by different types of radiation (e.g., alphas and betas) can differ in shape. As such, pulse shape analysis might be used to distinguish the different radiation types.
- ➢ The pulse shapes might differ because the pulse rise time reflects the distribution within the detector volume of the deposited radiation energy and this distribution varies for different types of radiation.
- ➢ Pulse shape analysis can also be utilized to prevent two overlapping pulses from being misinterpreted as a single large pulse. This process is referred to as pile-up rejection.
- ➢ Individual (single) pulses coming out of an amplifier have a near-gaussian shape unlike overlapping pulses which can appear distorted.

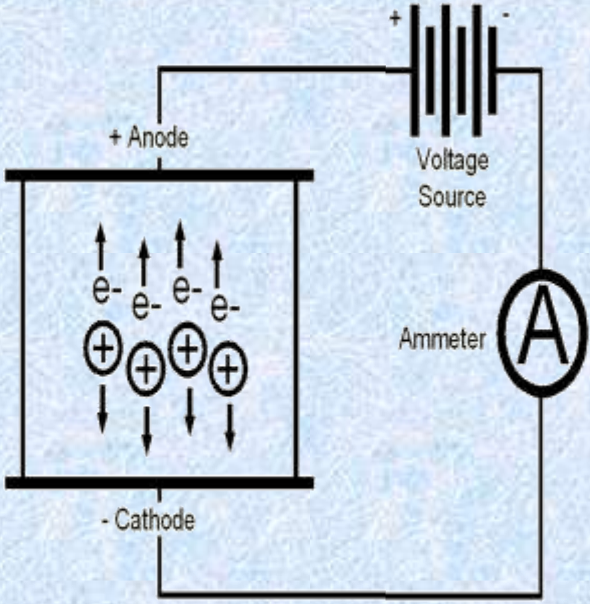
Two Main Principles of Radiation Detection

- Electrical collection of ions
  - ✓ Air Ionization
  - ✓ Gas Ionization
- Scintillation
  - ✓ Light Production

Gas-Filled Detectors

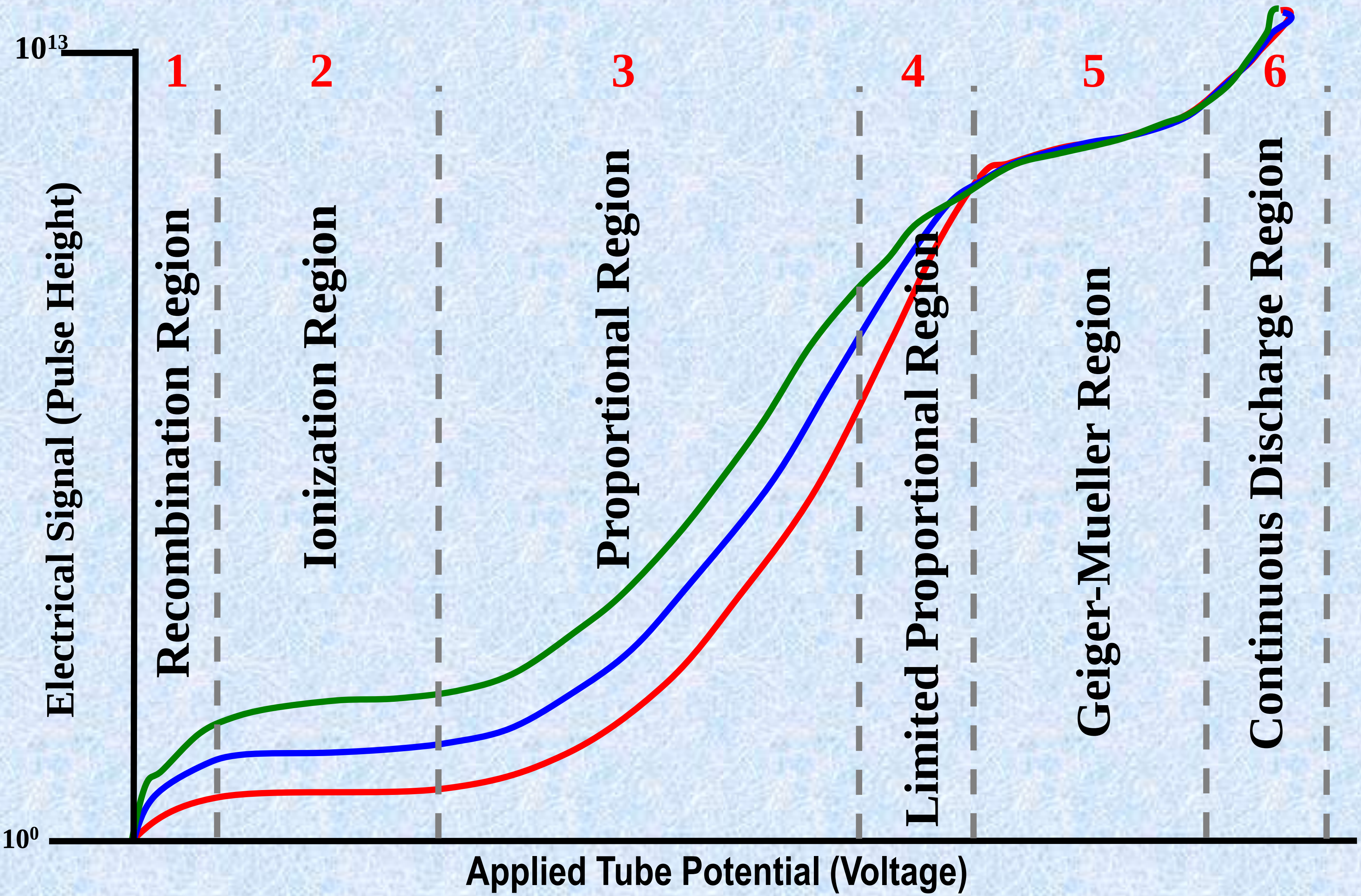
- Detect incident radiation by measurement of two ionization processes
  - Primary process: ions produced directly by radiation effects
  - Secondary process: additional ions produced from or by effects of primary ions
- Primary and secondary ions produced within the gas are separated by Coulombic effects and collected by charged electrodes in the detector
  - Anode (positively charged electrode)
    - ✓ Collects the negative ions
  - Cathode (negatively charged electrode)
    - ✓ Collects the positive ions
- Cylindrical gas chamber:
  - ✓ Air, P-10 gas mixture (10% methane, 90% argon), Helium, Neon





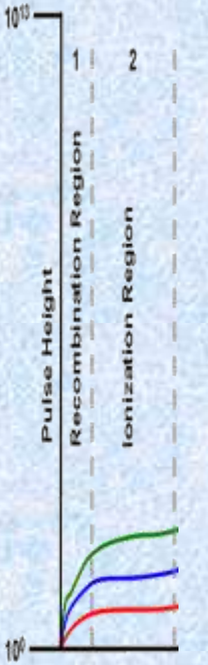
Gas Filled Detectors operation modes (6 stages)

α, β, γ each produce the same detector response



1. Recombination Region

- **Applied voltage too low** between the anode and cathode
- The ion pairs simply recombine before reaching the cathode or anode (**recombination occurs).**
- **The** response is minimal (l**ow electric field strength)** and not really valid for radiation detection.
- As voltage increases, the recombination's decrease and response increases.

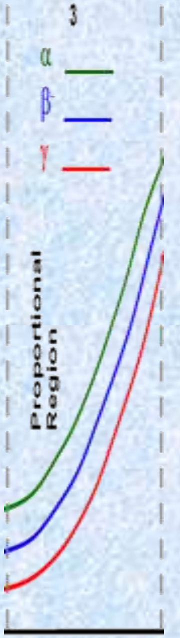


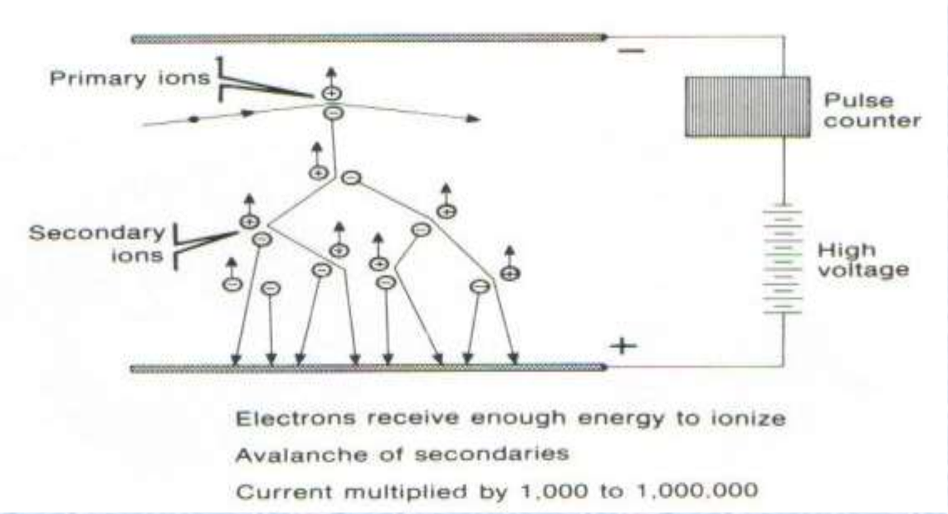
2. Ionization Chamber Region (Saturation Region)

- **In this region of operation for ionization chamber gas-filled detectors**
- **Voltage high enough to prevent recombination**
  - **All primary ion pairs collected on electrodes**
- **Voltage low enough to prevent secondary ionizations**
- **Voltage in this range called saturation voltage**
- **As voltage increases while incident radiation level remains constant, output current remains constant (saturation current)**
- **Two types of common nuclear medicine instruments operate in the ionization region: ionization chamber survey meters ("Cutie Pie") and dose calibrators.**
- **Ionization Survey meters are used to accurately measure exposure rates from usually a known source.**
- **Dose Calibrators operate similarly. Instead of air, they use sealed argon gas, since it is not affected by barometric pressure changes.**
- **Ionization chamber instruments are capable of measuring high levels of radioactivity.**

3. Proportional Region

- **Increasing the voltage of the system brings the output into the proportional region.**
- **Ionized electrons cause additional ionization of the gas. However, this is proportional to the amount of the original ion pairs produced.**
- **This is termed: Gas amplification (or multiplication) occurs**
- **In the proportional region, the increased voltage causes the ions to move with increased kinetic energy (increases primary ion energy levels) toward the electrodes.**
- **These energized electrons collide with other gas atoms and form additional ion pairs (Secondary ionizations occur).**
- **The increased voltage affects these ion pairs also, and the effect is amplified (total collected charge on electrodes).**





4. Limited Proportional Region

- An unusable region along this scale (Not very useful range for radiation detection)
- Collected charge becomes independent of # of primary ionizations
- Secondary ionization progresses to photoionization (photoelectric effect)
- Proportionality constant no longer accurate
- Here the avalanche is so severe that output no longer is proportional to the amount or energy level of the ionizing events.
- **Advantage:** detecting individual radiation events and detect non-penetrating radiation like α and β

5. Geiger-Mueller (GM) Region

- Any radiation event strong enough to produce primary ions results in complete ionization of gas
- After an initial ionizing event, detector is left insensitive for a period of time **(dead time)**
  - ✓ Freed primary negative ions (mostly electrons) reach anode faster than heavy positive ions can reach cathode
  - ✓ Photoionization causes the anode to be completely surrounded by cloud of secondary positive ions
  - ✓ Cloud “shields” anode so that no secondary negative ions can be collected
  - ✓ Detector is effectively “shut off”
  - ✓ Detector recovers after positive ions migrate to cathode
- These properties are used to construct a sensitive detector.
- Dead time limits the number of radiation events that can be detected.
- A GM survey meter operates in this region and is a useful tool for detecting and searching for often unknown sources of radiation.

6. Continuous Discharge Region

- Electric field strength so intense that no initial radiation event required to completely ionize the gas
- Electric field itself propagates secondary ionization
- Complete avalanching occurs
- No gas-filled detectors use this region.

MAJOR TYPES OF DETECTORS

❑ ionizing and non-ionizing radiation detectors are :

✓ **Gas Detectors**
  - **Ionization Chambers**
  - **Proportional Counters**
  - **Geiger-Mueller Tubes (Geiger Counters)**

✓ Scintillation detection (**Inorganic and Organic Scintillators)** and

✓ **Semiconductor/**Solid-state **Detectors**

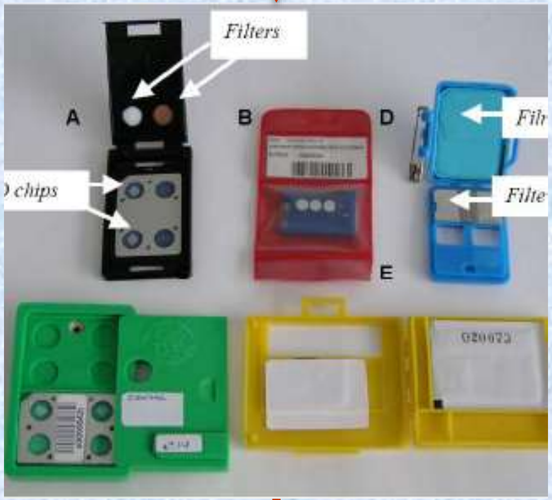
Radiation monitoring instruments are distinguished into:

Area survey meters (or area monitors)

Gas filled detectors:

- ➢ Ionization chambers
- ➢ Proportional counters
- ➢ Geiger-Mueller (GM) counters

Personal dosimeters (or individual dosimeters)



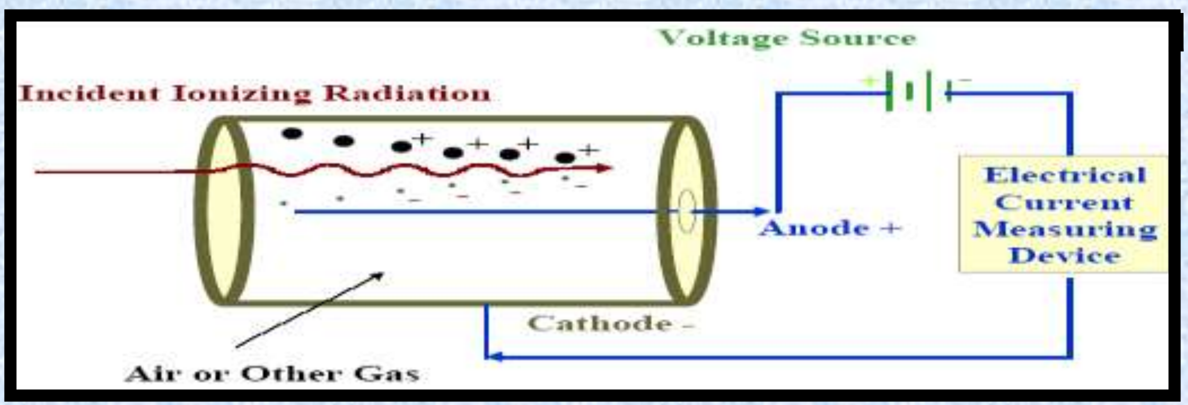
Solid state detectors:

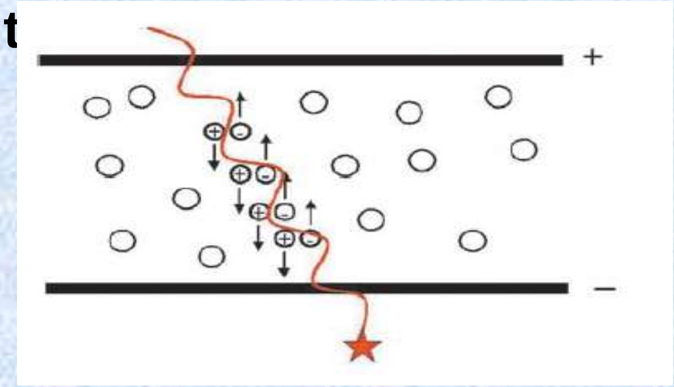
- Scintillator
- Semiconductor detectors

Ionization Chamber

- Ionisation chambers are used in radiation therapy and in diagnostic radiology for the determination of radiation dose. The dose determination in reference irradiation conditions is also called beam calibration.
- Ionisation chambers have various shapes and sizes depending upon the specific requirements.
- An ionisation chamber is basically a cavity surrounded by a conductive outer wall and having a central collecting electrode. The wall and the collecting electrode are separated with a high quality insulator to reduce the leakage current when a polarizing voltage is applied to the chamber.
- A guard electrode is usually provided in the chamber to further reduce the chamber leakage. The guard electrode intercepts the leakage current and allows it to flow to ground bypassing the collecting electrode.

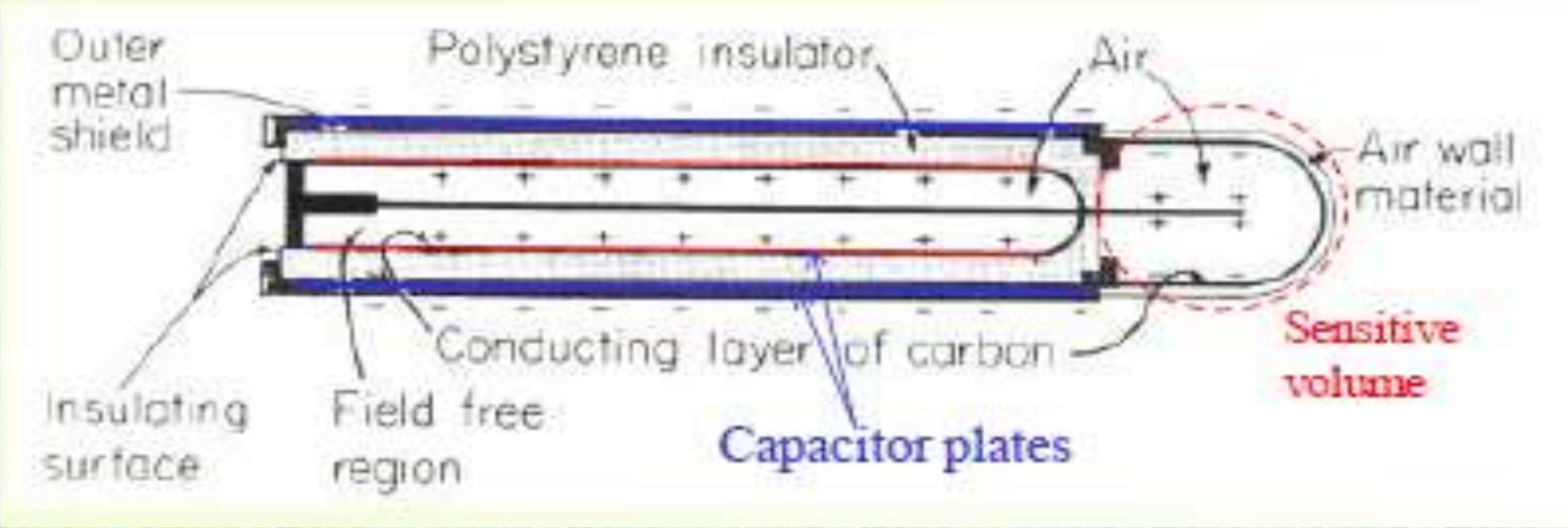
- **An ionization chamber basically consists of a gas volume, cylindrical container between two electrodes connected to a high voltage (100 V to 1000 V).**
- The wall and the collecting electrode are separated with a high quality insulator to reduce the leakage current when a polarizing voltage is applied to the chamber.
- **Anode (+) : Wire at center of chamber, Cathode (-): Chamber walls**
- **The exact value of this voltage is a function of the type of gas, the gas pressure, and the size and geometric arrangement of the electrodes**
- **Operating Principles**
  - **Voltage applied across electrodes**
  - **Incident radiation (α, β, or γ) enters chamber and ionizes the fill-gas**
  - **Ions (+/-) separate and migrate to respective electrodes**
  - **The number of electrons collected by the anode will be equal to the number produced by the primary ionizing particle**





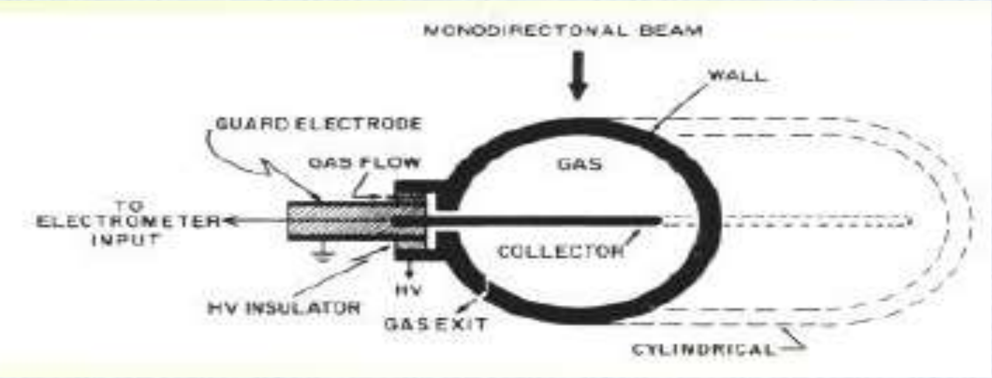
Condenser type chamber

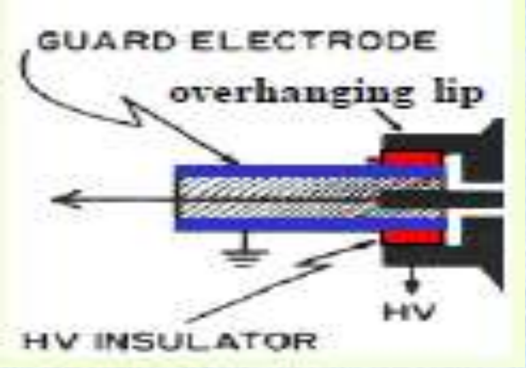
- Operates without external connections while being irradiated
- The chamber electrodes are connected in parallel with a capacitor, built into the stem of the chamber.
- Ions are produced in both of the air compartments, but are collected only in the chamber, reducing the voltage and charge of the capacitor.

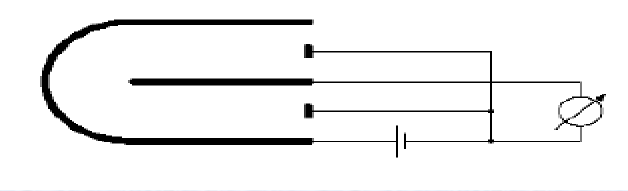


Cylindrical (thimble) ionisation chamber

- The wall material is of low atomic number Z, i.e., tissue or air equivalent of the thickness less than 0.1 g/cm^2.
- The chamber construction should be as homogenous as possible, although an aluminum central electrode (1 mm in diameter) **and a cylindrical chamber wall with a spherical or conical end mounted on a cylindrical stem.**
- Thimble chambers are irradiated at right angles to the stem axis in monodirectional beams.
- The high voltage (HV), usually 200-500V, is applied to the chamber wall, with the collector connected to the electrometer input at or near ground potential







Spark chamber

Definition:

- Spark chambers consist of a stack of metal plates placed in a sealed box filled with a gas such ashelium, neonor a mixture of the two.

Operation:

- When a charged particle ray travels through the box, it ionizes the gas between the plates.
- Ordinarily this ionization would remain invisible.
- However, if a high enough voltage can be applied between each adjacent pair of plates before that ionization disappears, then sparks can be made to form along the trajectory taken by the ray in effect becomes visible as a line of sparks.
- In order to control when this voltage is applied, a separate detector (often containing a pair of scintillator splaced above and below the box) is needed.
- When this trigger senses that a ray has just passed, it fires a fast switch to connect the high voltage to the plates.
- The high voltage cannot be connected to the plates permanently, as this would lead to arc formation and continuous discharging.

Drift chamber

Definition:

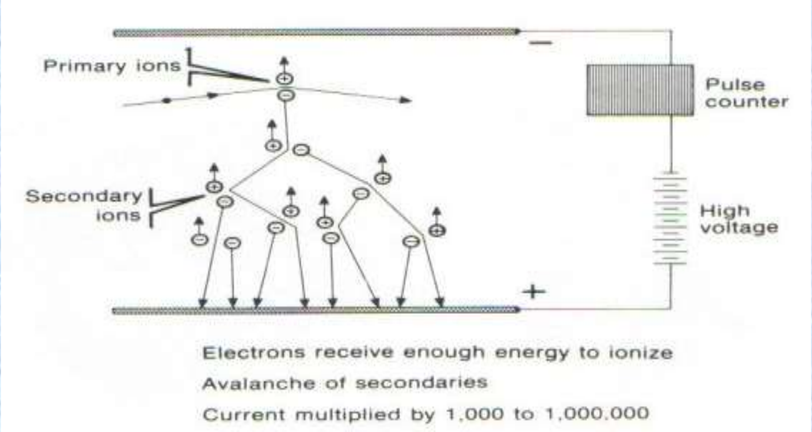
- Drift chamber is a proportional chamber, where the distances between the wires fell to the range of 10 cm.
- Drift chamber is a special proportional chamber.

Operation:

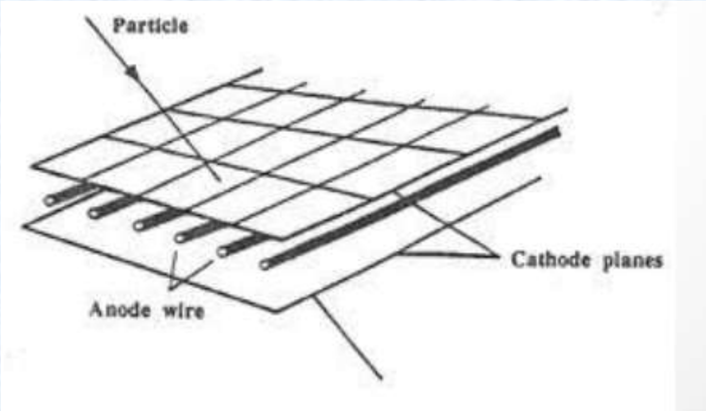
- There is proportionality between the position of the generated ion column and the time interval needs for collecting ions by the anode wire.
- This proportionality can be used for precise describing of the position of the particle trace.
- By time measurement = position of the penetrating particle can be characterized = coordinate detector
- Electric field must be kept homogeneous. Path –flying time connection (proportionality) is linear.

Proportional counter

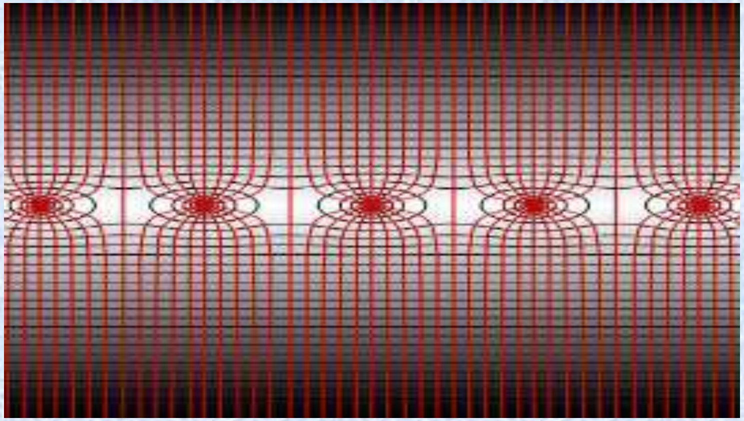
- **A proportional counter is a modified ionization chamber.**
- **Operation: The detector is filled by natural gas. Free electrons moving by high electric field can excite the gas molecules.**
- If the electric field is big enough, then the electrons can absorb energy during two elastic collisions. The energy is equal to the ionization potential of the gas. During the coming collision every electron can ionize an atom. After this process the original electron and a new (just generated from ionization) electron will propagate. These two electrons can ionize one-one atom (in other words two atoms), and after the process another plus one-one electron will be generated. Etc…
- Avalanche of electrons can be generated this way. The strength of the avalanche and the measured electric signal are proportional to the number of the primer electrons. After this effect the name is: proportional counter. (There is a gas which brakes the avalanche to grow up to infinity strength.)



- Numerous proportional counters are installed in a flat container.
- Numerous wires are outspreaded parallel to each other in the flat container. These are the anode wires.
- Above and below the theoretical planes of the wires solid metal planes are installed. These metal planes are the cathode planes.
- The gas fill is joint, but every single wires can work as independent proportional counters.



- Structure of the electric fieldinside the proportional chamber:



- Gas counters may be constructed in any of the three basic geometries: Parallel plate, cylindrical, Spherical.

- Parallel plate:

  The electric field (E) is = Vo/d

- Cylindrical chamber:

  The electric field (Er) is = [Vo/ln(b/a)] x l/r

where

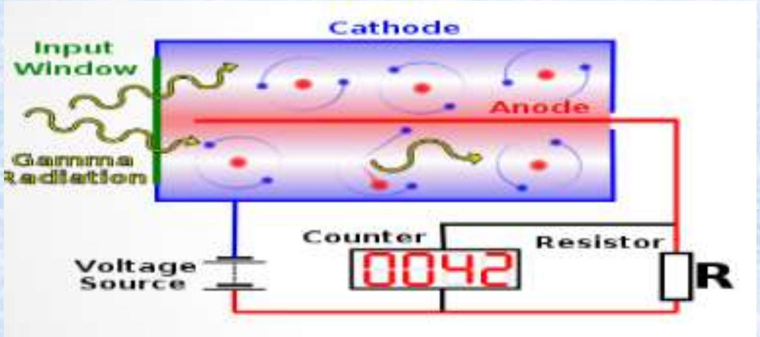
Vo	=	voltage applied
d	=	distance between the parallel plates
a	=	radius of the central wire
b	=	radius of the counter
r	=	distance from the center of counter.

Geiger –Müller-counter

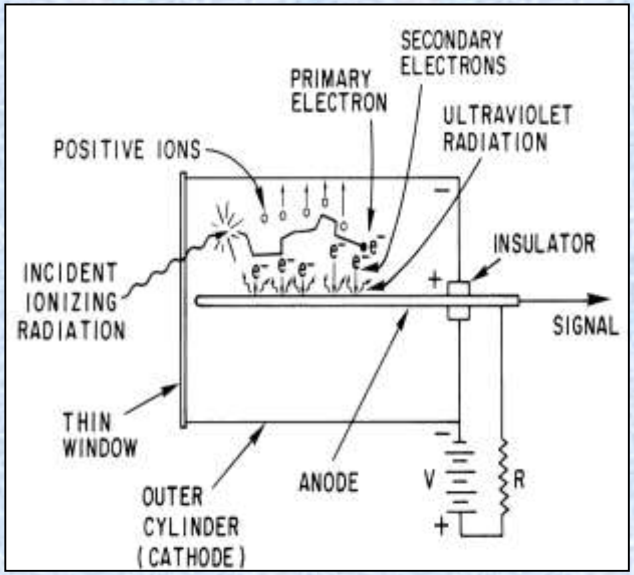
- A Geiger counter uses a Geiger-Müller tube and some kind of counter
- The Geiger-Muller tube is full of gas (argon, helium, and neon), this gas becomes ionised when radiation hits (it is very good for detecting alpha particles).
- The counter counts how many times this happens per minute (or second)
- The spark in the gas can be amplified and sent through a speaker to give the "clicking" sound

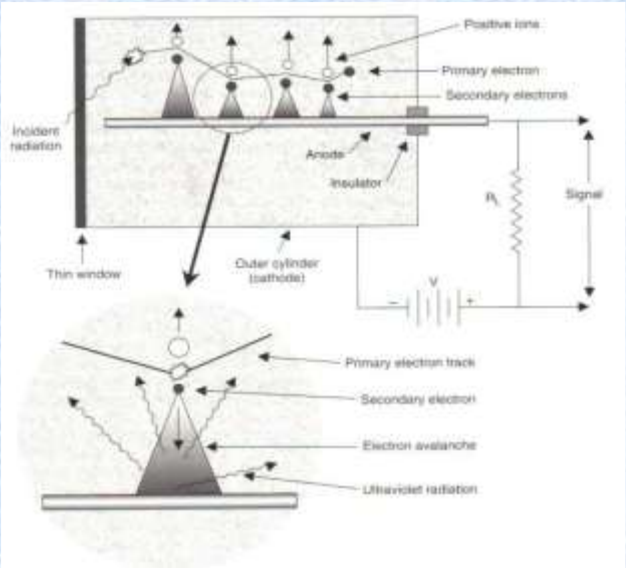
Operation: **If the power of a proportional chamber is increased above the normal operating power, a threshold can be reached, where the gas amplification will grow up to infinite value. In this case, the discharge generated by one electron is going to be self-supported. If the discharge will be extinguish externally, a new type of counter can be designed: penetration of the propagating particle elicits the electron pulse (the effect), but the strength of the effect will be independent of the energy of the particle.** It is possible to find a mixture of gas fill to get a trigger counter. It means that the counter goes back to starting position after one discharge cycle.

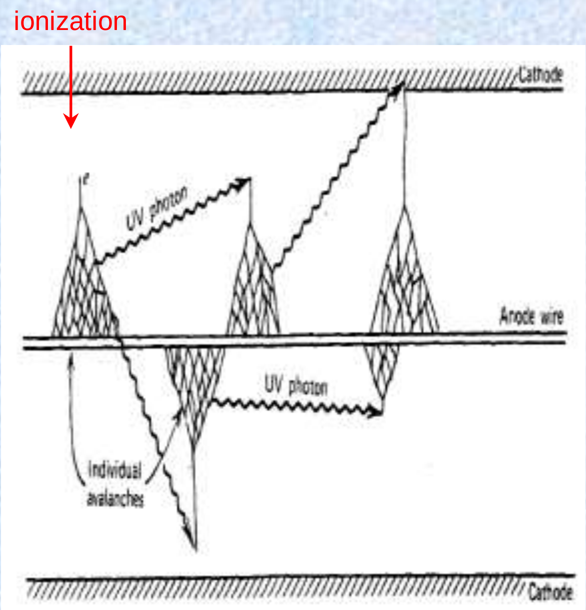
G-M survey meters are useful for low-level β particle and γ ray survey work, and they may also be used to monitor neutrons.



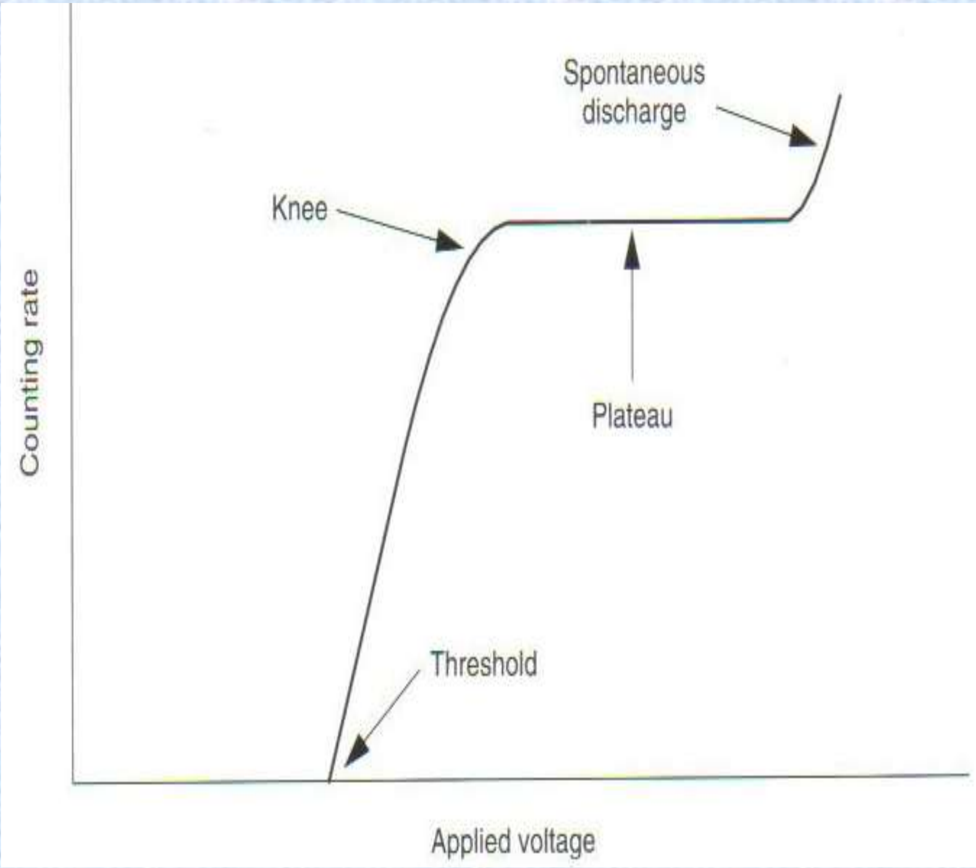
- **Increase the high voltage beyond the proportional region will eventually cause the avalanche to extend along the entire length of the anode**
- **The size of all pulses - regardless of the nature of the primary ionizing particle- is the same**
- **When operated in the Geiger region, therefore, a counter cannot distinguish among the several types of radiations**
- If the applied voltage is further increased, gas amplification is so great that a single ionizing particle produces a ionization avalanche.
- Each output pulse of current has the same magnitude and no longer reflects any properties of the incident radiation.







Counting Curve of a GM Meter



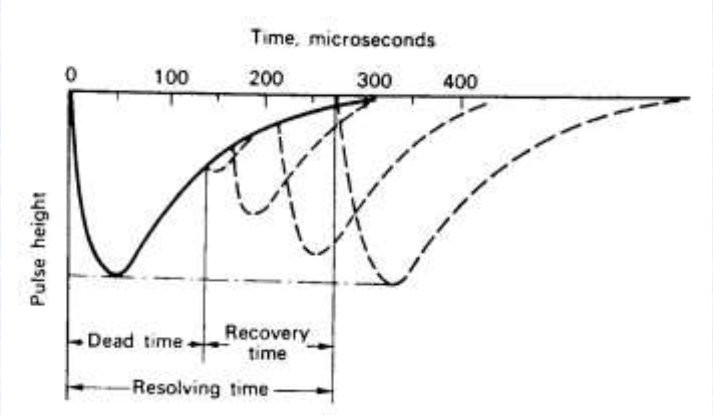
- **Threshold:** the level of voltage at which the electrodes are charged enough to detect incident radiation.
- At a certain voltage, a plateau is reached (the knee) and increases in voltage will not affect the count rate for the same amount of radiation.
- At very high voltages, there is a breakdown in the composition of the gases and there is a steep rise in spontaneous discharges.
- At this level there can be permanent damage to the device.

Quenching a Geiger Counter:

- After the primary Geiger discharge is terminated, the positive ions slowly drift away from the anode wire and ultimately arrive at the cathode or outer wall of the counter. Here they are neutralized by combining with an electron from the cathode surface. In this process, an amount of energy equal to the ionization energy of the gas minus the energy required to extract the electron from the cathode surface (the work function) is liberated. If this liberated energy also exceeds the cathode work function, it is energetically possible for another free electron to emerge from the cathode surface---and thereby produce a spurious count
- Prevention of such spurious counts is called quenching
- External quenching: electronically, by lowering the anode voltage after a pulse until all the positive ions have been collected
- Internal quenching: chemically, by using a self-quenching gas

Resolving Time:

- The negative ions, being electrons, move very rapidly and are soon collected, while the massive positive ions are relatively slow-moving and therefore travel for a relatively long period of time before being collected
- These slow-moving positive ions form a sheath around the positively charged anode, thereby greatly decreasing the electric field intensity around the anode and making it impossible to initiate an avalanche by another ionizing particle. As the positive ion sheath moves toward the cathode, the electric field intensity increases, until a point is reached when another avalanche could be started
- **Dead time:** The time required to attain this electric field intensity
- **Recovery time:** The time interval between the dead time and the time of full recovery
- **Resolving time:** The sum of the dead time and the recovery time



Dead Time and Recovery Time of GM Tubes:

Dead Time:

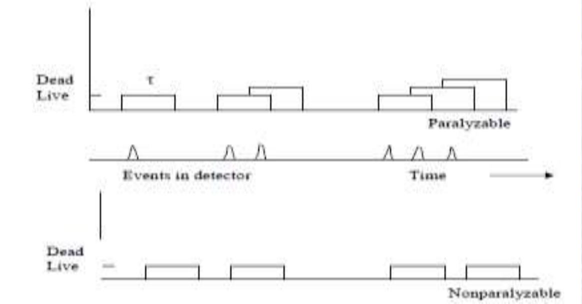
- In nearly all detector systems, there will be a minimum amount of time that separates two events in order that they may be recorded as two separate pulses.
- In some cases the limiting time may be set by processes in the detector itself, while in other cases the limit may arise due to the delays associated with the electronics.
- This minimum time separation is usually called the dead time of the counting system.
- Because of the random nature of radioactive decay, there is always some probability that a true event will be lost because it occurs too quickly following a preceding event.
- Two models of dead time are in common use, categorized on the basis of paralyzable and nonparalyzable response of the detector.
- If the system dead time is τ, and the measured count rate is m , then the true count rate n predicted by the two models can be expressed as

Nonparalyzable Model:

$$n = \frac{m}{1 - m\tau}$$

Paralyzable Model:

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



Recovery Time of GM Tubes:

- Pulses occur when one ionizing event follows another at an interval too short for the counter to have completely recovered.
- This situation due to the fact that the positive ion sheath has not reached the cathode when the second ionizing event occurs.
- The longer the interval between the ionizing events the larger the second pulse will be, until it reaches its maximum.
- The time interval between the first full pulse and the delectability of another full pulse depends on the characteristics of the counter tube and is known as resolving time.
- This time interval is made up of two parts:
    - ✓ The first part is the dead time and is the time after a count during which no pulse can be registered at all, even if an ionizing event occurs, because the electric field has collapsed and has not yet been reestablished.
    - ✓ The second part is the recovery time, a time of increasing sensitivity, during which an ionizing event will give a pulse of amplitude less than that which is characteristic of the particular tube at the applied voltage.
- During this time the electric field is growing to its maximum value.
- At the end of the recovery time a full pulse is recorded.

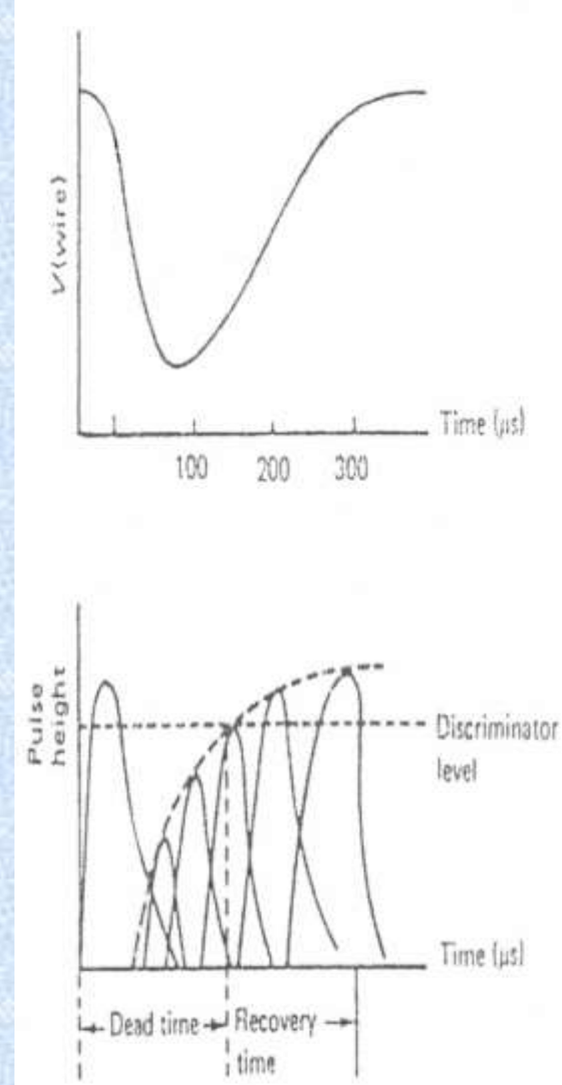
Consider two radioactive sources of strength S1 and S2.
Let n1, n2 be the respective count rates recorded and n12 be the count rate recorded when sources are taken together.
Let τ be the resolving time.
Let N1, N2 and N12 be the corrected count rates respectively.
Then we have

$$N_1 = \frac{n_1}{1-n_1\tau};\ N_2 = \frac{n_2}{1-n_2\tau};\ N_{12} = \frac{n_{12}}{1-n_{12}\tau}$$

We have N1 + N2 = N12

substituting value of N1, N2 and N12 and solving in the above equation and neglecting the higher powers of τ we get

$$\tau = \frac{n_1 + n_2 - n_{12}}{2n_1 n_2}$$



Advantages and Disadvantages

G-M tube: Advantages

- Variety of sizes and shapes
- Inexpensive
- The slightest radiation event strong enough to cause primary ionization results in ionization of the entire gas volume
- Thus detector is highly sensitive, even in lowest intensity radiation fields
- Only simple electronic amplification of the detector signal is required
    - Hardware lasts longer
    - Requires less power
- Strong output signal means G-M needs less electrical noise insulation than other detectors

G-M tube: Disadvantages

- Incapable of discerning between type and energy of the radiation event
- Only counts events and yields output in events per unit time or dose rate
- A beta particle or gamma ray, high or low energy, represents one event counted
- Only capable of detecting fields to some upper limit of intensity

Geiger-Mueller Vs Gas-Filled Detectors

Advantages

- highly sensitive: capable of detecting low intensity radiation fields
- Only simple electronic amplification of the detector signal is required
- less insulation required to decrease “noise” interference

Disadvantages

- No single detector setup can discriminate between α, β, γ
- no energy discrimination
- entire gas volume ionizes
- magnitude of resultant pulse lengthens detector “dead time
- limited use in extreme intensity radiation fields (> 40 R/hr)

Features of area survey meters:

- “Low battery” visual indication.
- Auto zeroing, auto ranging, auto back-illumination facilities.
- Variable response time and memory to store the data values.
- Option for both the ‘rate’ and the ‘integrate’ modes of operation.
- Analog or digital display, marked in conventional (exposure/air-kerma) or recent “ambient dose equivalent” or “personal dose equivalent” units.
- Audio indication of radiation levels (through the ‘chirp’ rate).
- Re-settable / non-re-settable alarm facility with adjustable alarm levels.
- Visual indication of radiation with flashing LEDs.