Interactions of Nuclear Radiation with Matter

PH3105 - Autumn 2024
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What to deal with in this course?

- Nuclear radiation: beta and gamma rays
- Radiation detector: Geiger-Muller counter and scintillation counter
- Important attribute of nuclear radiation: High energy particles (a few 100s keV to a few 10s MeV)
- How radiation is detected?
  - Through the interaction of nuclear radiation with matter
- What happens when radiation passes through matter?
  - Radiation interacts with matter and losses energy (partially or fully) to the matter

Why study this?

- Helps to understand how much damage a radiation can cause to living bodies and nonliving materials/devices
- Helps to design necessary safety protocols
- Interactions of nuclear radiation with matter, loss of energy of the incident radiation in these processes, and the effects produced in the matter through these interactions form the basis of radiation detection devices
- Knowledges of these interactions are essential to design the detectors, and to improve upon their sensitivity and efficiency
- Important for fundamental research in high energy physics

Preliminary notes

- Incident radiation sees the matter in terms of its basic constituents, i.e., as an aggregate of electrons and nuclei (and sometimes their constituents as well)
- Type of interactions depend upon the type of radiation and their energy
- We will classify the types of radiations in to following broad categories:
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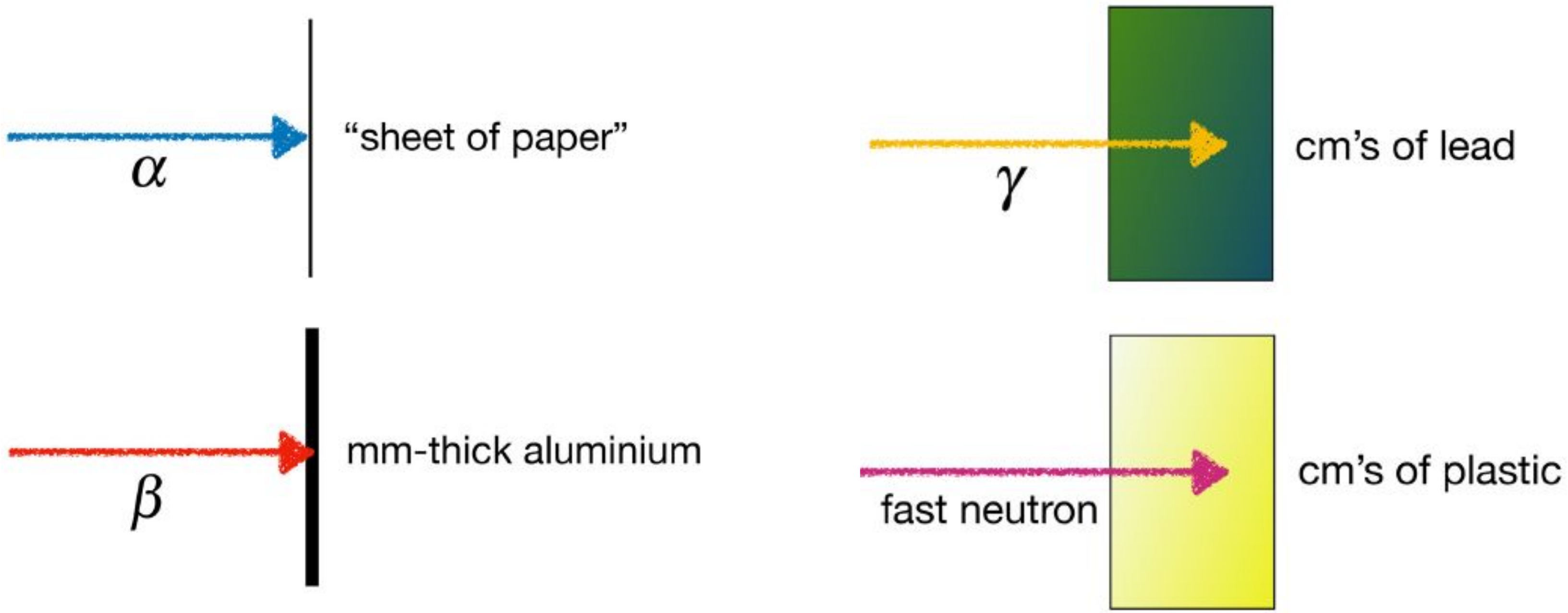
Charged Particulate Radiations
Heavy charged particles (characteristic distance $\cong 10^{-5}$ m)
Fast electrons (characteristic distance $\cong 10^{-3}$ m)

Uncharged Radiations
Neutrons (characteristic length $\cong 10^{-1}$ m)
X-rays and gamma rays (characteristic length $\cong 10^{-1}$ m)

Schematics showing typical ranges for different radiations



Measure of interaction strength

- Linear stopping power (also known as specific energy loss)
    - $S(E) = -\frac{\mathrm{d}E}{\mathrm{d}x}$ Defined as the energy loss per unit path length traversed by the incident radiation at a given energy
- Range of a radiation at a given energy
    - It is a measure of the penetration depth a radiation particle can cover in a material before getting stopped (losing all its energy) inside a material
    - The range of a particle stopping in a material, Δx can be evaluated by integration of the reciprocal of the stopping power, $S(E)$ from the incident energy down to zero:
    - $\Delta x = \int_0^{E_0} \frac{1}{S(E)} \mathrm{d}E$

Measure of interaction strength

- Stronger interaction means larger $S(E)$ and shorter Δx

How energetic charged particles lose energy in a medium

- By collision (Coulomb scattering) with
    - the orbital electrons of the atoms - dominant process
    - The atomic nucleus - generally insignificant as such collisions are rare and nuclee are much heavier than the incident radiation
- By bremsstrahlung radiation - radiation coming out from an accelerated charged particle

How energetic charged particles lose energy in a medium

- Upon entering in an absorbing matter, incident charged radiation Coulombically interacts simultaneously with many electrons of the matter
- Each of the electrons in the matter feels an impulse when charged radiation passes from its vicinity - the process is statistical in nature
- Depending on the proximity (strength) of the interaction,
    - the atomic electron may be raised to an higher-energy state (excitation)
    - the atomic electron may be ejected from the atom (ionization)
    - the ejected electrons may have significant kinetic energy - they are called δ-rays, which further loses energy following the above processes
- A small part of the energy of the incident radiation is transferred to the atomic electrons of the matter - velocity of the incident radiation decreases
- Maximum energy transfer in one collision: $4\mathrm{Em_0/M}$, $\mathrm{m_0}$ is the mass of an electron and E and M are respectively, the energy and mass of of the incident radiation

Interaction of beta (β) ray with matter

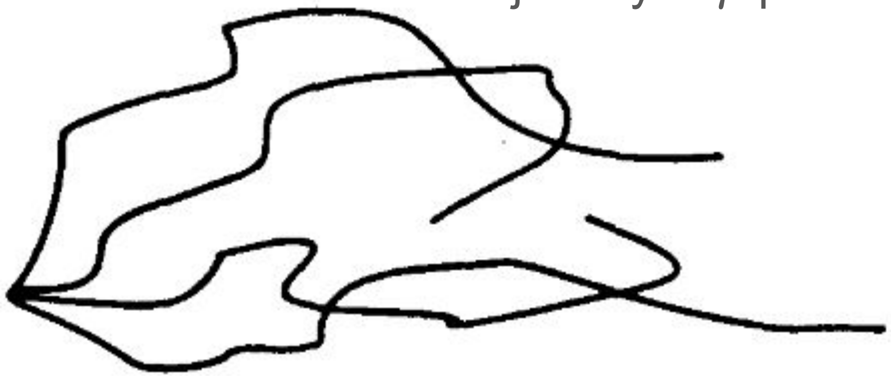
- Two types of beta (β) ray: β^- (electron) and β^+ (positron)
- They have same mass but opposite charge
- Positron is the antiparticle of electron and it is unstable

Interaction of fast electrons with matter

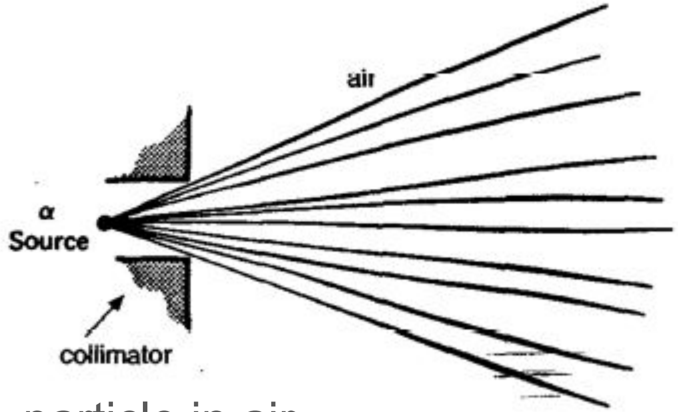
- Major energy loss mechanisms are through
  - Inelastic collision (Coulomb force) with bound atomic electrons (excitation and ionization) in the matter
  - Bremsstrahlung radiation - emission of electromagnetic radiation from accelerated charge in the electric field of atomic nucleus and electrons
  - The first one is dominant at low energies (up to a few MeV); the second process become important at higher energies (10s of MeV)
- The nature of inelastic collisions for fast electrons with bound atomic electrons is different from that of heavy charged particle radiation because of equal mass of interacting particles in the former case
  - Significant energy transfer per collison
  - Large deflection - large angle scattering - trajectory is not a straight line

Tortuous trajectory of fast electrons in matter

Trajectory of β particle in aluminum



In comparison, heavy charged particle mostly move in a straight path, until at the end of their range



Trajectory of α particle in air

Bethe-Bloch formula for energy loss by fast electrons

Specific energy loss by collision

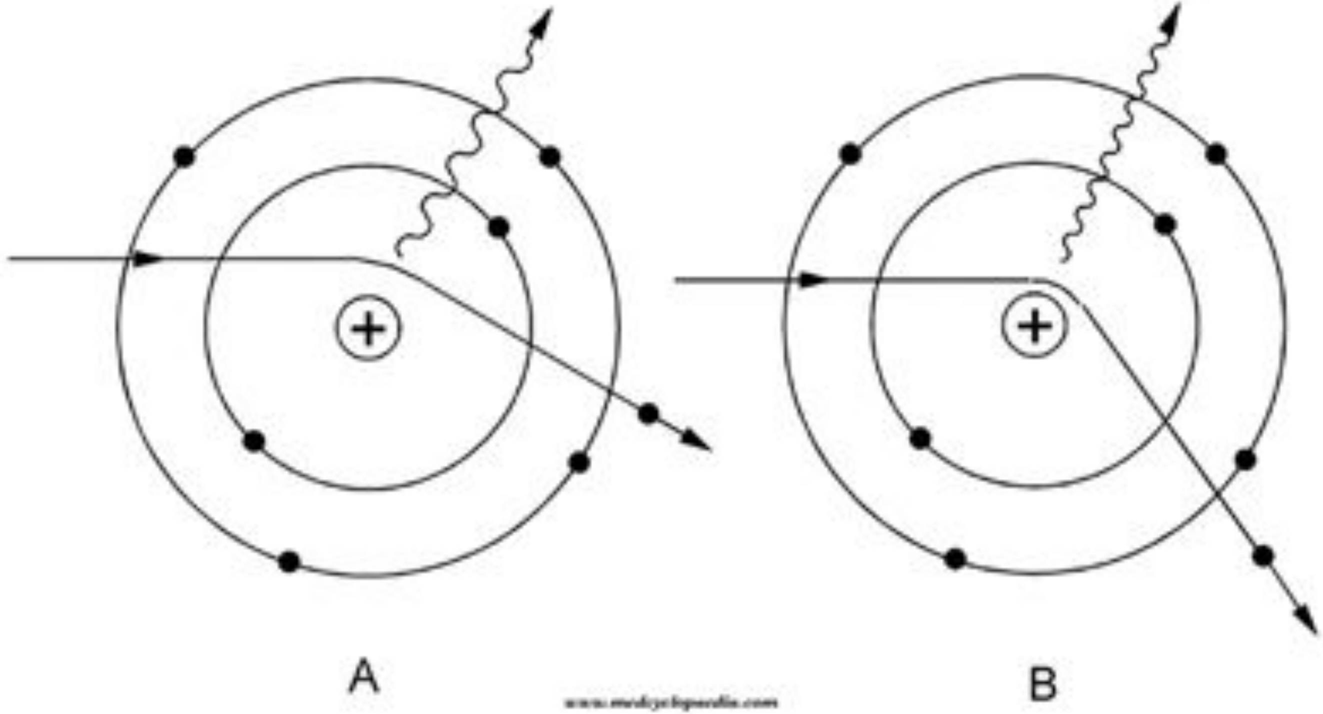
$$-\left(\frac{dE}{dx}\right)_c = \frac{2\pi e^4 NZ}{m_0 v^2}\left(\ln \frac{m_0 v^2 E}{2I^2(1-\beta^2)} - (\ln 2)(2\sqrt{1-\beta^2} - 1 + \beta^2) + (1-\beta^2) + \frac{1}{8}\left(1-\sqrt{1-\beta^2}\right)^2\right)$$

$$\beta \equiv v/c$$

Two important features:

(1) Specific energy loss is inversely proportional to energy of radiation
(2) It is linear in Z (atomic no.) of stopping material

Bremsstrahlung radiation loss



Energy loss due to Bremsstrahlung

Specific energy loss by Bremsstrahlung

$$-\left(\frac{dE}{dx}\right)_r = \frac{NEZ(Z+1)e^4}{137m_0^2c^4}\left(4\ln\frac{2E}{m_0c^2} - \frac{4}{3}\right)$$

Two important features:

(1) Specific energy loss is proportional to energy of radiation

(2) It is proportional to Z^2 (Z is atomic no.) of stopping material

Specific energy loss by Bremsstrahlung is negligible compared to that due to collision at low energies but it dominates at high energy of radiation

Comparison of energy loss due to Bremsstrahlung and collision

The ratio of specific energy losses by collision and by Bremsstrahlung is approximately given by (Here, energy E is MeV)

$$\frac{(dE/dx)_r}{(dE/dx)_c} \cong \frac{EZ}{700}$$

Comparison of specific energy loss at different energies

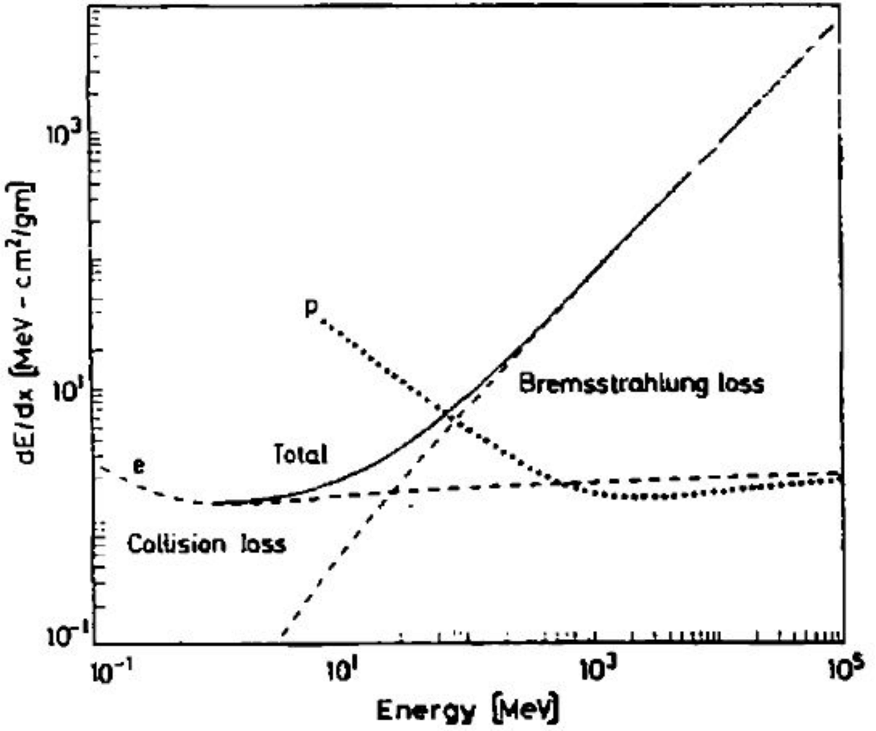


Fig. 2.10. Radiation loss vs. collision loss for electrons in copper. For comparison, the *dE/dx* for protons is also shown

Absorption of β^- in matter (energy is distributed)

$$\frac{I}{I_0} = e^{-nt}$$

I_0 = counting rate without absorber

I = counting rate with absorber

t = absorber thickness in g/cm^2

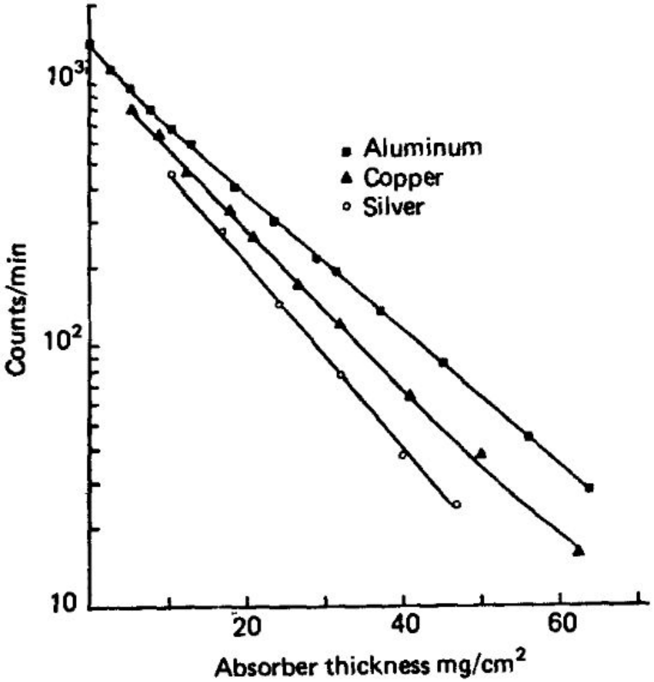


Figure 2.15 Transmission curves for beta particles from ^{185}W (endpoint energy of 0.43 MeV). (From Baltakmens.[25])

Energy loss by β^+ (positron)

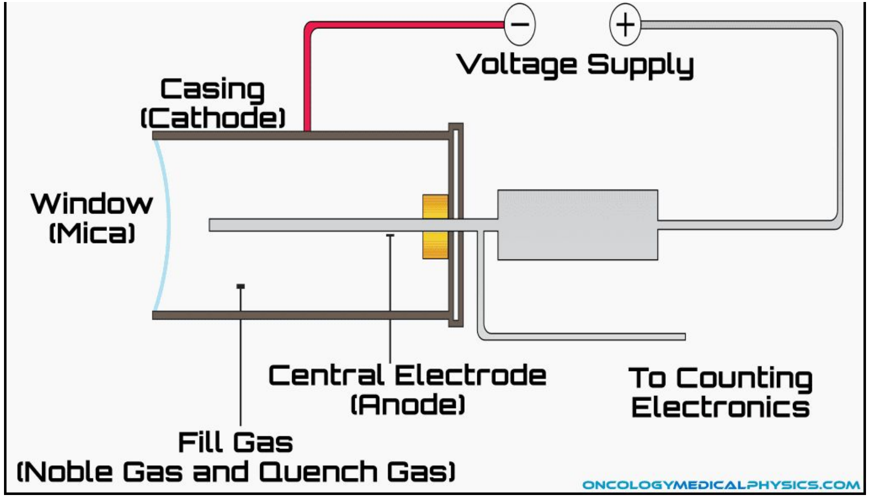
- Positions are unstable particles - undergo annihilation when meet with electrons - giving two gamma photons, each of energy about 0.5 MeV
  - Why two gamma photons?
- They can also from positronium (bound state of an electron and a positron) which is also unstable and eventually (in ps to ns) annihilates giving two 0.5 MeV gamma photons
- Gamma photons are long range - so energy can be deposited far away from the original position track

Principle of radiation detection

- Incident radiation losses energy to the stopping material through various interactions
- Energy loss eventually generates electron and positive ion pairs
- Collecting the electrons through an electrical circuit (applied bias) leads to a current pulse which can be amplified and detected electronically
- Detector performance depends on the ionization energy of the stopping material and mobility of electrons in the materials etc.
- One of the earliest and simplest radiations detectors are the gas filled detectors

Detection of high energy low mass charged particles (β-ray)

- Geiger-Muller counter: interacting matter is usually an inert gas



In the cylindrical geometry, electric field at a radial distance r from the center is

$$\mathscr{E}(r) = \frac{V}{r \ln(b/a)}$$

V = voltage applied between anode and cathode

a = anode wire radius

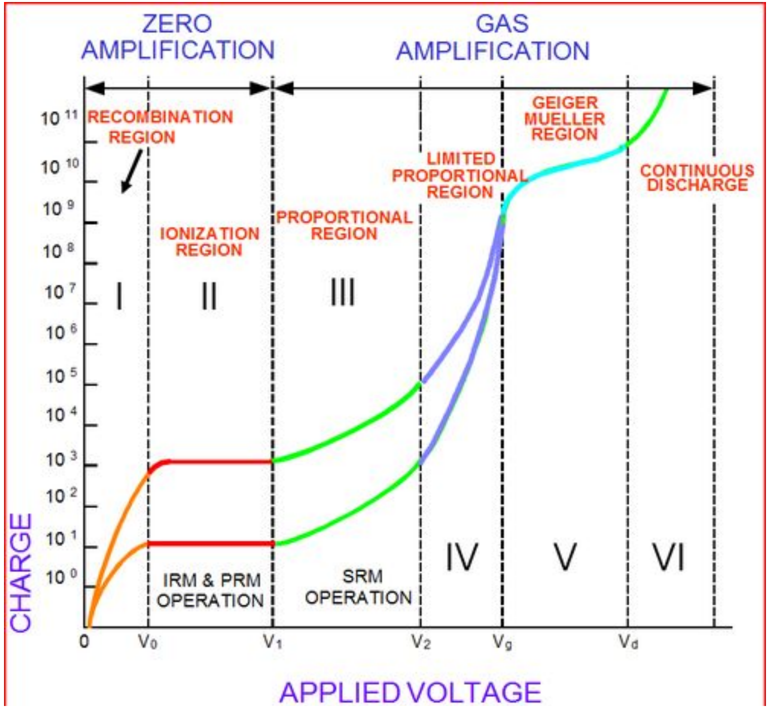
b = cathode inner radius.

For cylindrical geometry, V = 200 V, a = 0.01 cm, b = 1.0 cm, E(0.01 cm) ~ $5\text{x}10^6$ V/m
For parallel plate geometry with 1.0 cm gap, electric field is uniform and to get an electric field of $5\text{x}10^6$ V/m, more than 50000 V is needed!

Choice of fill gas

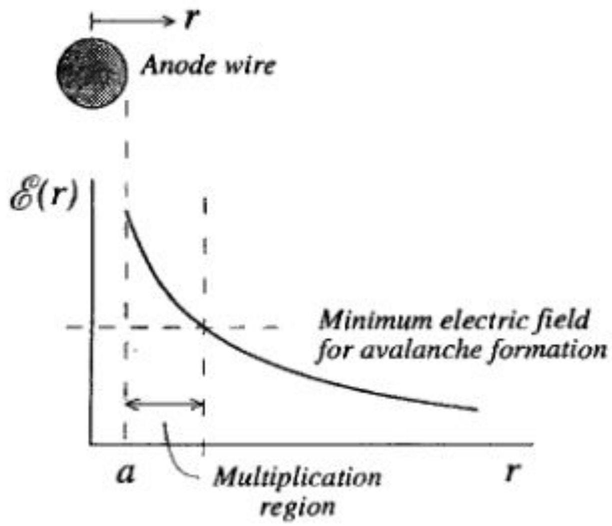
- Usually monatomic gas is preferred so that deposited energy is not dissipated in dissociating the molecule
- Inert (nobel) gas is chosen for their low electron affinity - they do not tend form negative ion
- Argon is most common fill gas: It is inert, stable (non-radioactive), abundant, inexpensive, reasonably high atomic no., works well with halogen quenching gas
- Small amount of quenching gas is mixed
    - What is it?

Different regions of operation of gas-filled detectors



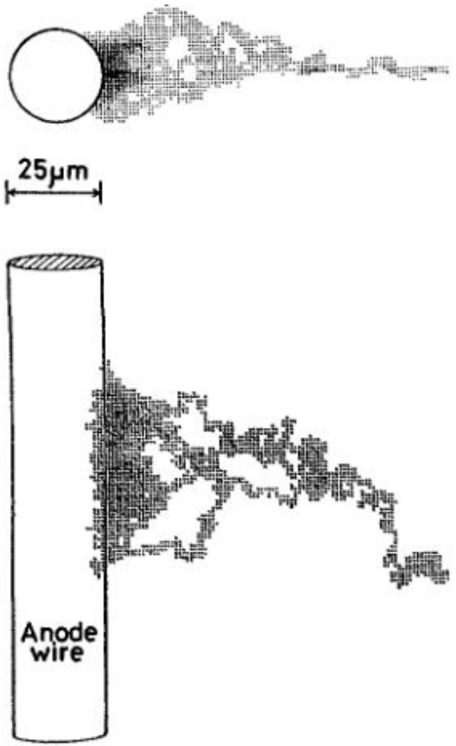
- Ion chamber and proportional counter both can detect radiation and can also provide an estimate of energy of incident radiation
- Ion chamber is less sensitive to fluctuation in applied voltage, but it has very low signal due to no intrinsic amplification
- Proportional counter has more signal amplitude due to intrinsic amplification, but it gives more noise due to fluctuation of applied voltage
- G-M counter has very high intrinsic amplification, but energy information is lost - it is very sensitive for radiation detection

Advantage of cylindrical geometry



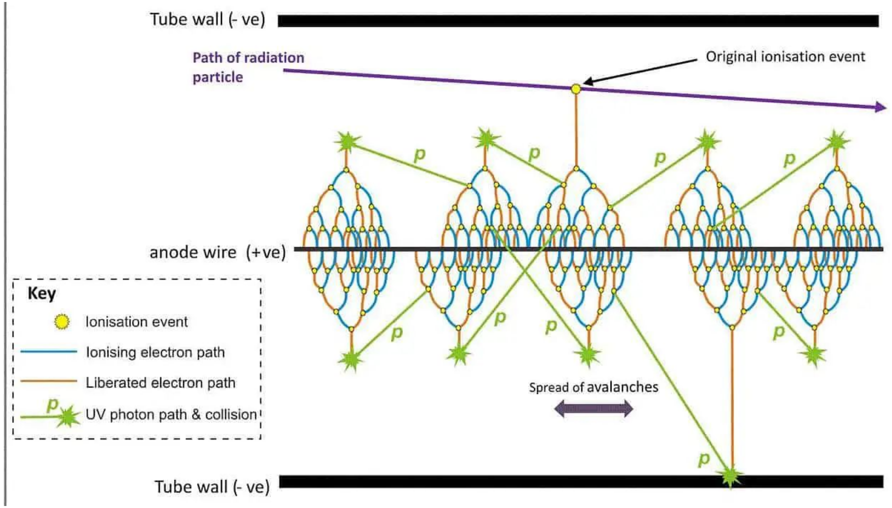
- Avalanche (amplification) takes place only in narrow region close to the anode wire - good uniformity

Townsend avalanches in proportional counter



- Each of the originally produced electron can produce their own avalanche and each of these avalanches are more or less uniform

Spread of avalanches in G-M tube



- The avalanches are self-limiting due to space charge effect of the positive ion cloud
- Avalanches stop when a certain amount of positive ions are accumulated!
- No. of electrons generated at the time of terminating avalanches are nearly same irrespective of initial ion pairs generated

Detection of γ-ray by G M counter

- Gas medium has very less probability of interaction with γ-ray photons
- Interaction γ-ray photons with the wall of the G M counter gives charged particle, that can interact with gas medium and be detected

What is quenching gas and why it is needed?

- To prevent multiple pulsing for one radiation event

Counting plateau in G-M tube