Fundamentals of Radiation Detection & Measurement

R. Redus, Chief Scientist, Amptek

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- R. Redus, Chief Scientist of Amptek, gave a presentation on "Electronics for Radiation Detection" at the "Short Course on Radiation Detection and Measurement", which was part of the 2017 IEEE Nuclear Science Symposium, in Atlanta, GA.
- This current presentation provides some background information on radiation detection, needed to understand the notes on electronics.
- The presentation on electronics is available online with additional tutorial information which has been added. A set of notes with additional info is also available.
- Amptek recommends these notes as an introduction to electronics for radiation detection and measurement and as a useful guide to many of Amptek's customers.

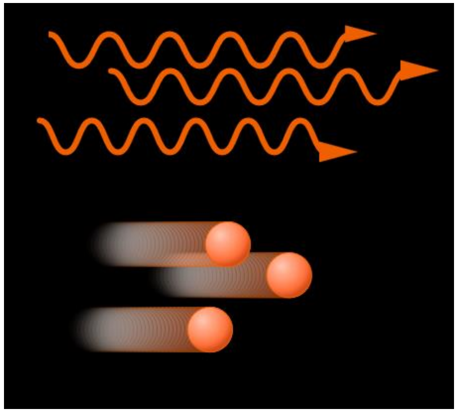
Outline

1. **Ionizing Radiation**
    1. *What is ionizing radiation?*
    2. *What do we measure?*
    3. *Why do we measure?*
2. **Types of ionizing particles**
    1. *Fast electrons*
    2. *Heavy ions*
    3. *Gamma-rays and X-rays*
    4. *Neutrons*
3. **Characteristics of Radiation Measurements**
4. **Radiation Detectors**
    1. *Gas-filled*
    2. *Semiconductors*

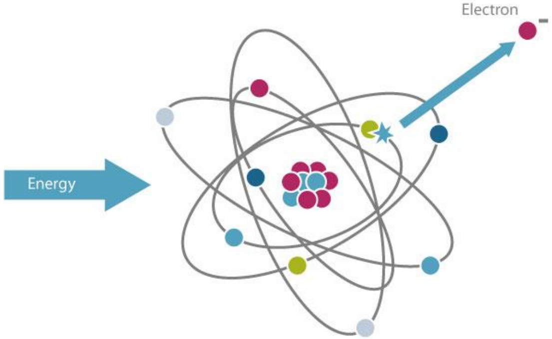
1. Ionizing Radiation

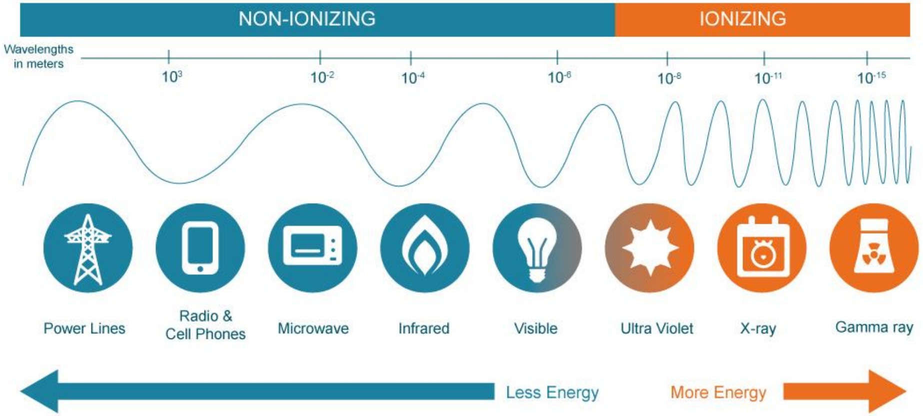
Introduction

- **What is radiation?**
  - *Transmission of energy in the form of waves or particles*
    - Radio waves, light, magnetic forces, sound
    - Anything that moves energy between objects



- **What is ionizing radiation?**
  - *Particles or waves that carry enough energy to ionize, i.e. to remove electrons from an atom*

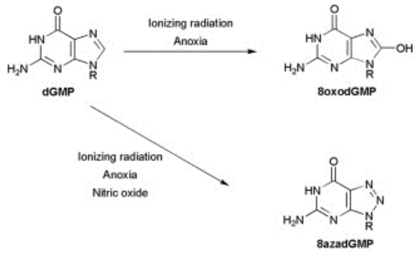




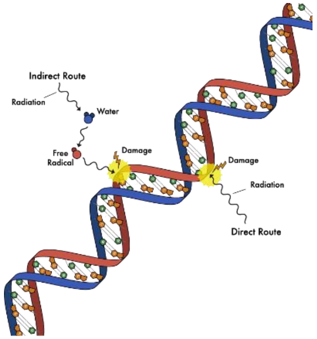
Introduction

Ionization is key

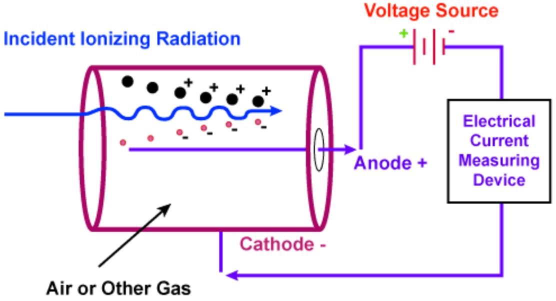
- *Ionization is the key to its risks*
  - Ionization causes chemical reactions
  - Reactions in cells interfere with metabolism
  - Reactions in DNA interfere with genetics



- *Ionization is the key to its use*
  - Medical, materials analysis, research



- *Ionization is the key to its detection*
  - Humans cannot directly detect ionization
  - Radiation detection equipment measures ionization, directly or indirectly
  - Ionization → Electric charge is produced. We detect electric charge



Introduction

Why do we measure radiation?

- *Safety*
  - Is radiation above a threshold?
  - Dose, dose rate in medicine, reactors, etc
- *Medicine*
  - Imaging: X-rays, SPECT, PET, CT
  - Radiation therapy for cancer
- *Industry*
  - Attenuation is used to measure thickness
  - X-ray spectra used in material analysis: XRF, XRD,
  - Sterilization
- *Research*
  - Understand materials (batteries, biochemical)
  - Understand nuclei, high energy particles

Introduction

What properties of radiation do we measure?

- *Presence of radiation*
  - Is there any present (above a threshold)?
- *Amount of radiation*
  - Flux – Number per cm^2 per sec   Fluence – Number per cm^2
  - Dose – Energy deposited per gram
  - Radiation damage – Dose x damage factor
- *Type of radiation*
  - Alpha particle, beta particle, X-ray, neutron, muon, …
- *Energy, time of interaction, position, …*
  - Many other quantities could be of interest
  - Often measure the distribution (or spectrum) of energy, time, position, ….

Introduction

Units

- *Energy: eV*
  - 1 eV is energy gained when one electron crosses potential of 1 volt
  - 1 eV = $1.6\text{x}10^{-19}$ joules

    Very small! Drop paperclip by 1": $3\text{x}10^{-4}$ joules
  - eV ~ energy of chemical reactions
  - keV ~ energy of ionization
  - MeV ~ energy of nuclear transitions
  - GeV ~ rest energy of protons and neutrons

- *Flux: particles/cm^2-sec*
  - Note that we are counting individual quanta

Introduction

Radiation safety

- *Dose: Rad*
  - Dose is energy deposited per unit volume
  - 1 Rad = 100 erg/gram = 0.01 joule/kilogram
- *Health effects*
  - "REM" is Rads x damage factor
  - 1 Gray = 100 Rads   1 Sievert – 100 REM
- *What matters?*
  - 0.05 millirem – dose from typical dental X-ray
  - 1.0 millirem – average daily dose from natural background
  - 600 millirem – average dose from CT or fluoroscopy
  - 80 rem – given slowly – increases chance of cancer by 1%

Introduction

- **Radiation is a natural part of our environment**
  - Uranium, thorium in rocks, ^{40}K in rocks
  - Food contains ^{40}K and ^{14}C
  - Cosmic rays

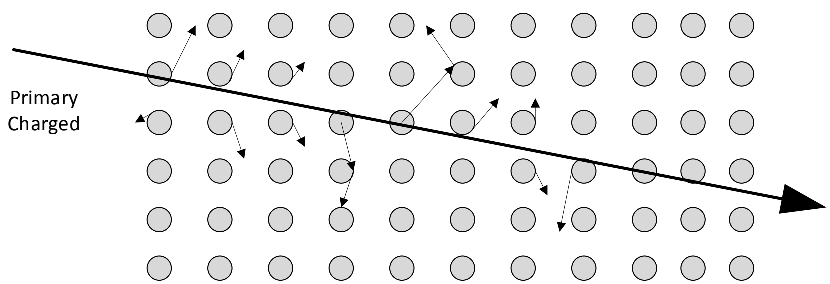
- **Radiation is not exotic or foreign, it's just that we cannot directly sense it. We need detectors.**

2. Types of Ionizing Radiation

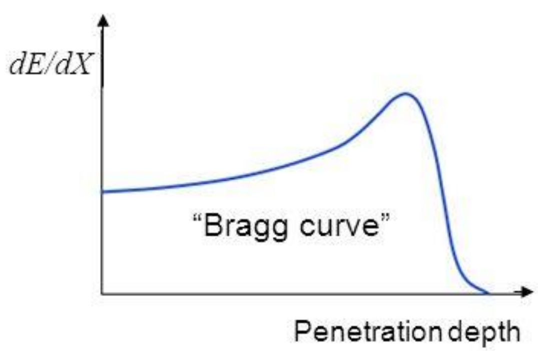
Types of radiation

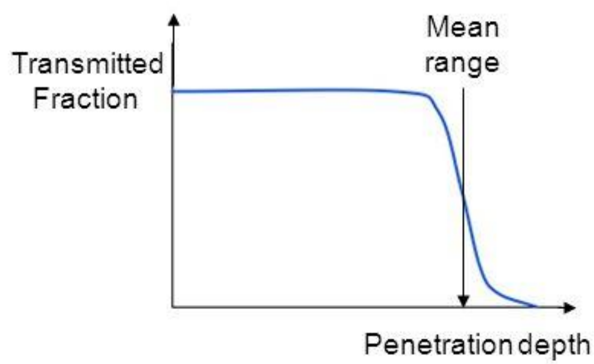
Directly Ionizing Particles

- Electrically charged
- As charged particle passes atoms, rips electrons away, leaving ionized atoms



- Continuously lose energy (slow down) like bullet fired into styrofoam
- Definite range (no particles go past some fixed depth)

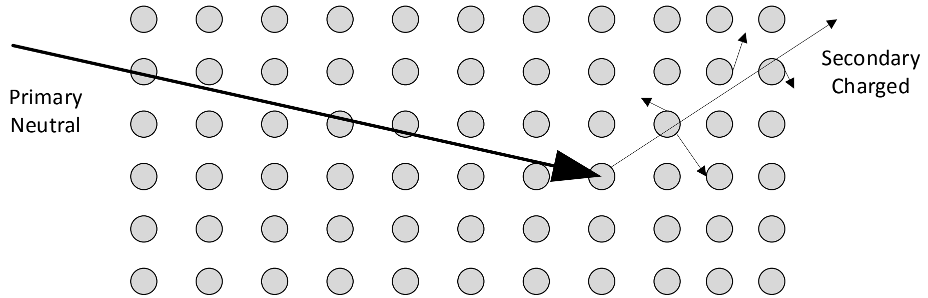




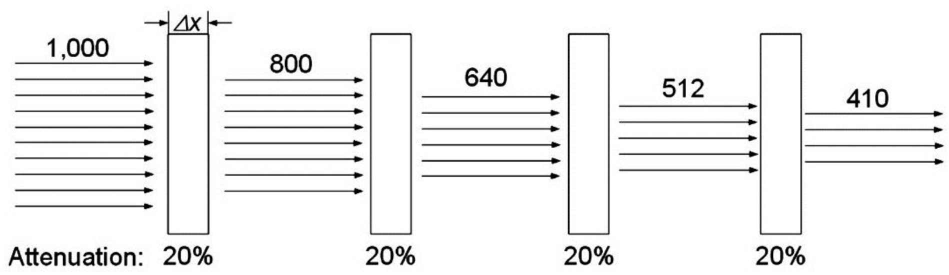
Types of radiation

Indirectly Ionizing Particles

- Electrically neutral
- Pass through matter w/o interacting, then collide, producing charged secondary



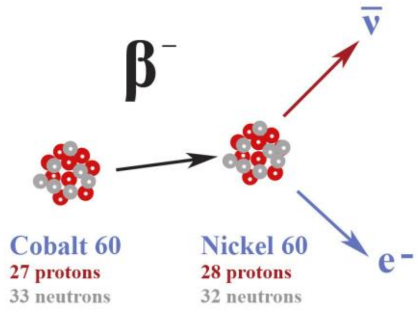
- Continuous loss of number of particles (intensity) but no change of energy
- Attenuated with depth but no definite range

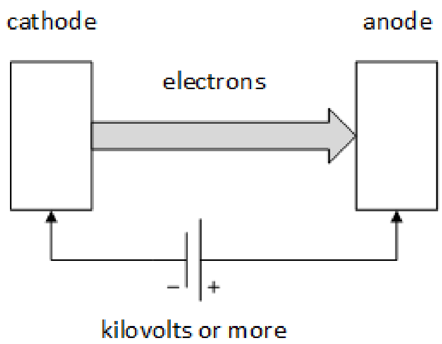


Types of radiation

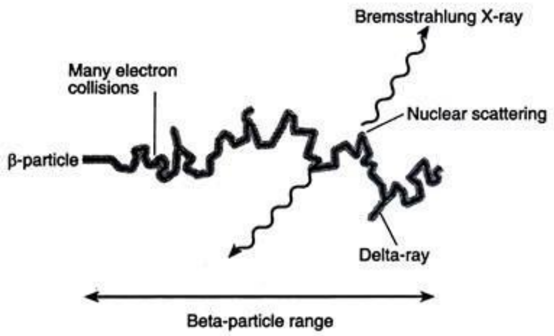
Fast electrons

- *Electrons with energy enough to ionize, e.g. > few keV*
- *Production*
  - Processes inside a nucleus: beta decay produce **beta particles** (electrons)
  - Accelerating voltage of kilovolts (or more)





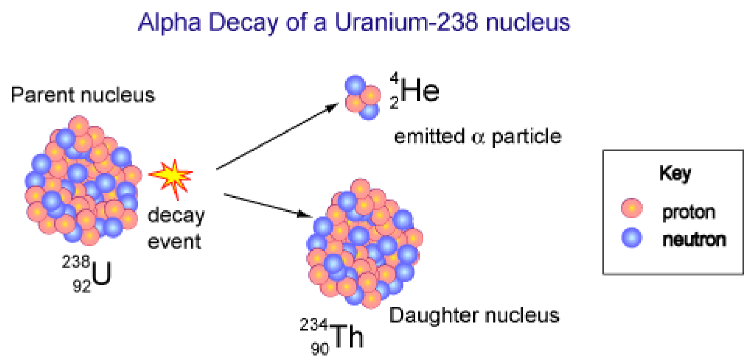
- *Directly interacting*
  - Lose energy continuously.
  - Range is ~ mm/MeV in solids
  - Beta particles stopped by 1-2 mm Al, plastic
  - Electrons have low mass, so scatter a lot



Types of radiation

Heavy ions

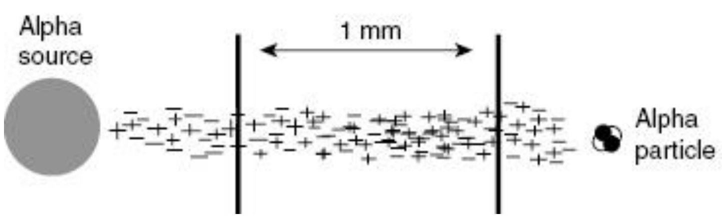
- *Production*
  - Processes inside a nucleus: alpha decay
  - High energy accelerators produce protons, pions, etc



- *Directly interacting*
  - Lose energy continuously but massive

    Like cannonballs in lettuce

    Lots of damage along a short track



  - Range is ~ microns/MeV.
  - Alpha particles ~10 microns, one sheet of paper
  - Little scattering, high ionization density

Types of radiation

Stopping of charged particles

- *Ionization loss: Bethe-Bloch formula*

$$\left\langle \frac{dE}{dx} \right\rangle_{ion} = \left(\frac{4\pi}{m_e c^2}\right)\left(\frac{Z\rho}{A}\right)\left(\frac{q_{ion}{}^2}{\beta^2}\right)\left(\frac{N_A}{M_u}\right)\left(\frac{N_A q_e^2}{4\pi\varepsilon_0 M_u}\right)^2\left[\ln\left(\frac{2m_e c^2\beta^2}{\varepsilon_{ion}\left(1-\beta^2\right)}\right)-\beta^2\right]$$

  - *dE/dx* is energy lost per length, the "stopping power"
  - Increases with density of the absorber
  - Increases as $q_{ion}{}^2$

- *Radiative loss*

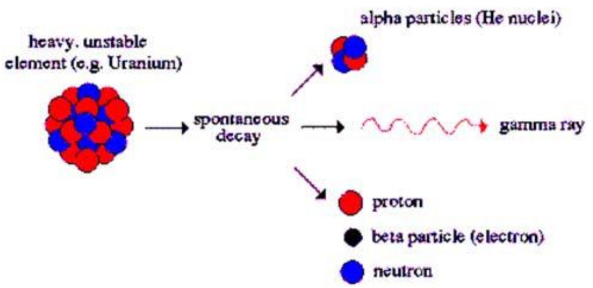
$$\left\langle \frac{dE}{dx} \right\rangle_{rad} = E\left(NZ\left(Z+1\right)\right)\left(\frac{q_e^4}{137 m_e^2 c_4}\right)\left[4\ln\left(\frac{2E}{m_e c^2}\right)-\frac{4}{3}\right]$$

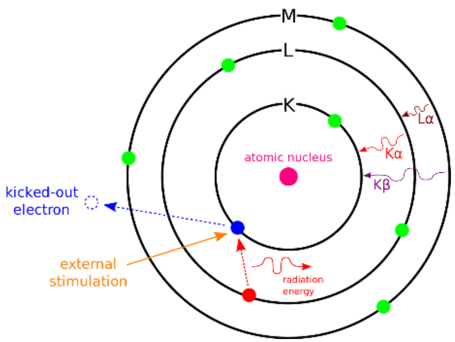
  - Important for electrons

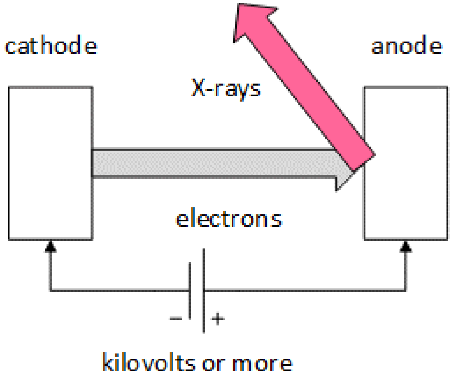
- *Cerenkov radiation*
  - Occurs when particle exceeds speed of light in the medium
  - Light a sonic boom but electromagnetic
  - Gives the classic "blue glow"

Types of radiation

- **Electromagnetic (Gamma-rays and X-rays)**
  - *Production*
    - Gamma-rays are produced inside a nucleus
    - X-rays are produced outside a nucleus: electron transitions or voltage (kV and up)

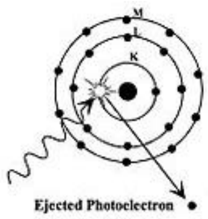






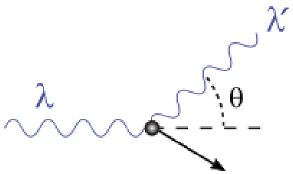
  - *<u>Indirectly</u> interacting*
    - Exponentially attenuate beam. Some penetrate deeply
    - Attenuation length microns (low energy X-rays) to centimeters of lead (γ-rays)
    - A photon interacting with an atom produces a secondary electron, which produces the ionization we measure

- **Stopping of X-rays and gamma-rays**
  - *Photoelectric absorptions*
    - All of the energy of the photon is transferred to an electron



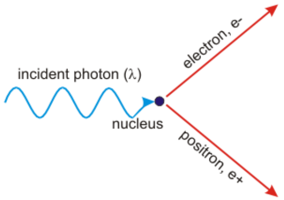
$$P_{photoelectric} \sim \frac{\rho Z^{4-5}}{E_{photon}^{3.5}}$$

  - *Compton scattering*
    - Only transfers a portion of the energy to the photon



$$E_{photon} = \frac{E_{incident}}{1+\left(\frac{E_{incident}}{m_e c^2}\right)(1-\cos\theta)}$$

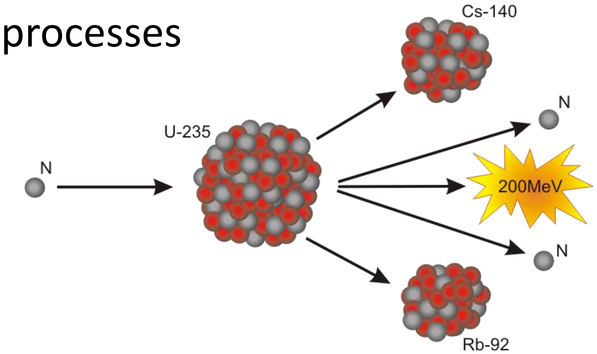
  - *Pair production*
    - Gamma-ray produces an electron-positron pair
    - Only possible above 1022 keV (2x electron rest mass)



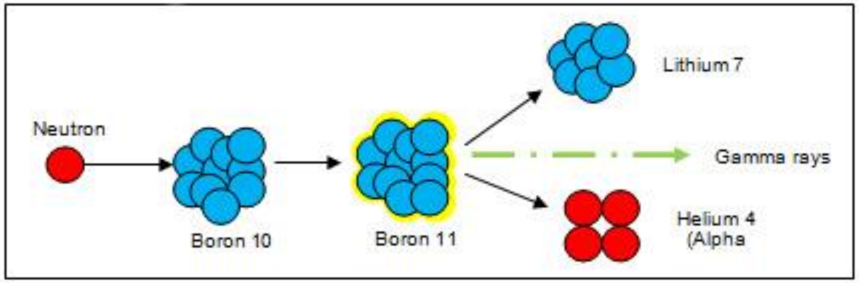
Types of radiation

Neutrons

- *Production*
  - Only produced in nuclear processes

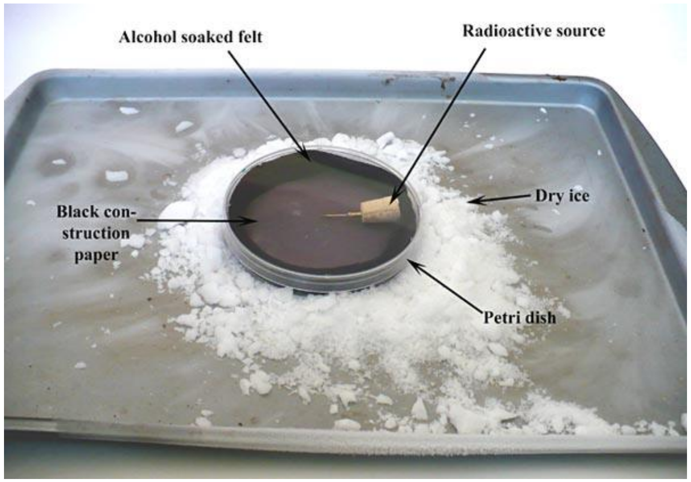


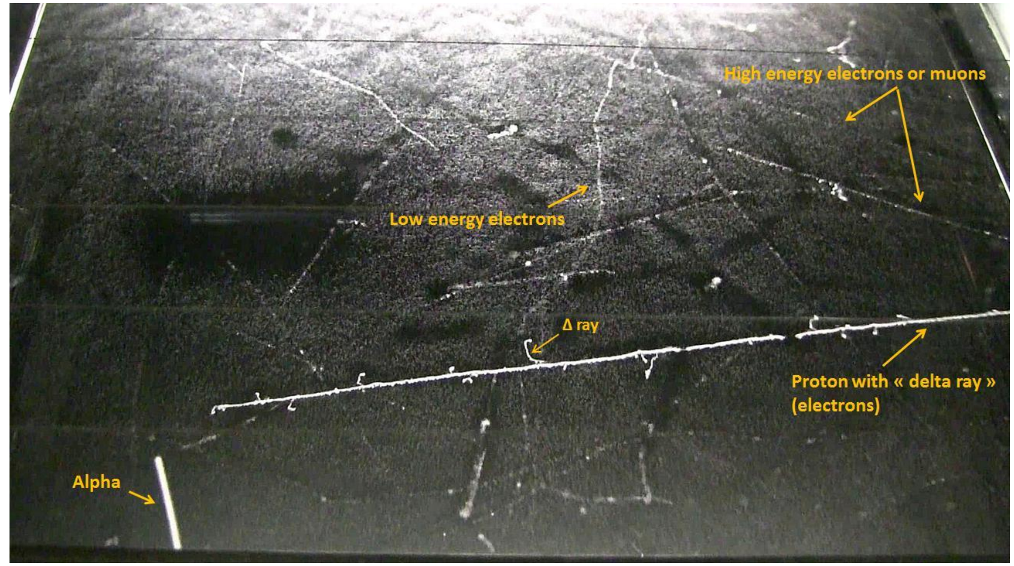
- *Indirectly interacting*
  - Exponentially attenuate. Stopped by meters of material with hydrogen
  - A neutron interaction is a nuclear reaction. It produces a secondary alpha and/or gamma-ray, which produces the ionization we measure
  - It changes the original atom (transmutation) so can produces radioactive atoms

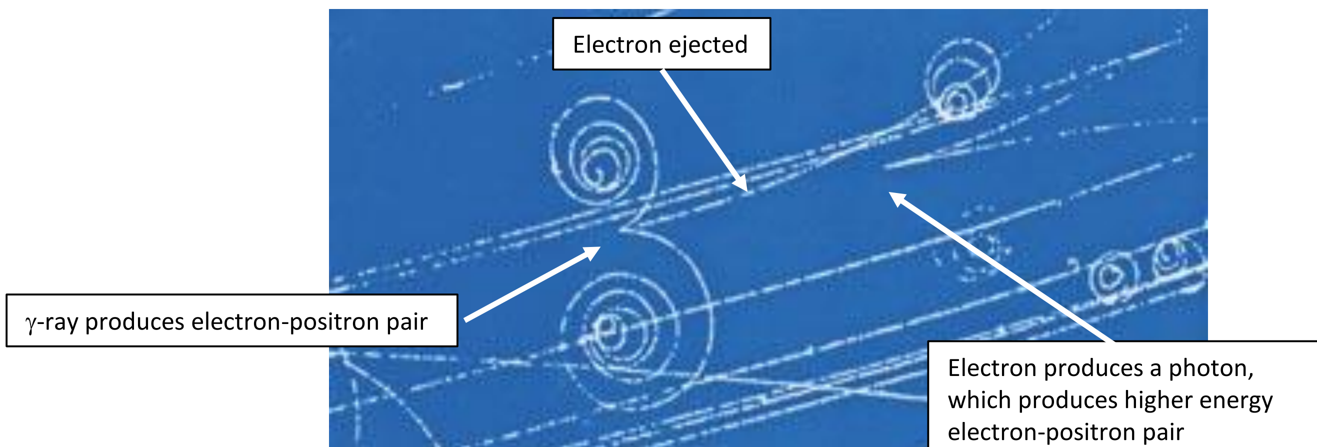


Types of radiation

- **Bubble chamber**





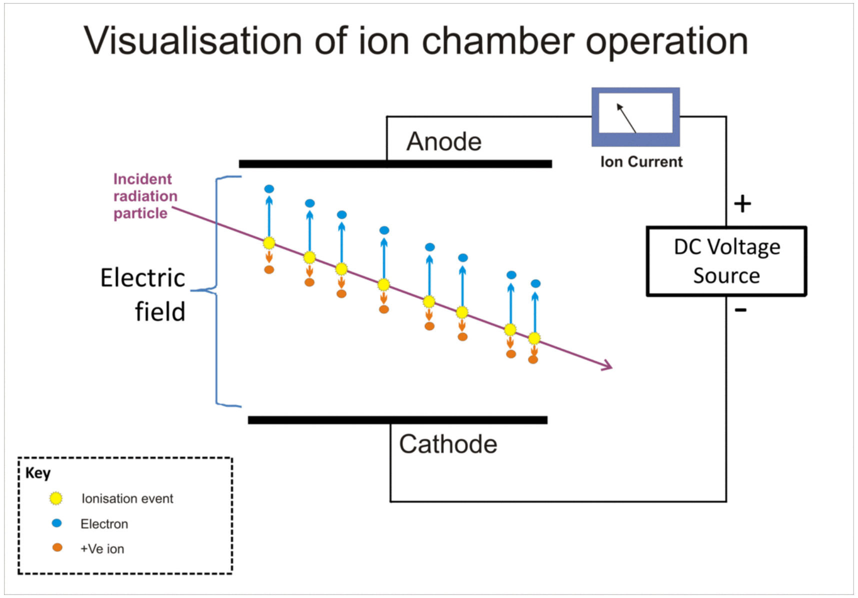


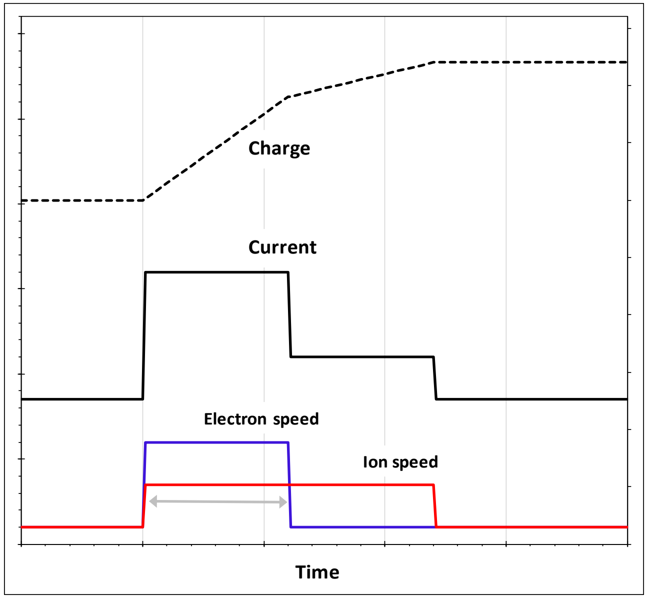
3. Characteristics of Radiation Measurements

Gas-Filled Detectors

Ion chamber

- *Charge formation*
  - Requires ~25 eV to create an electron-ion pair (depends on gas)
  - 5 keV X-ray → 200 ions while 5 MeV α → 200,000 ions
- *Current*
  - Bias voltage → electric field → moving charges → electric current $$I = Nq_e v$$
  - Velocity depends on bias voltage, pressure, and the gas
  - Current pulse: flows until charges reach electrodes

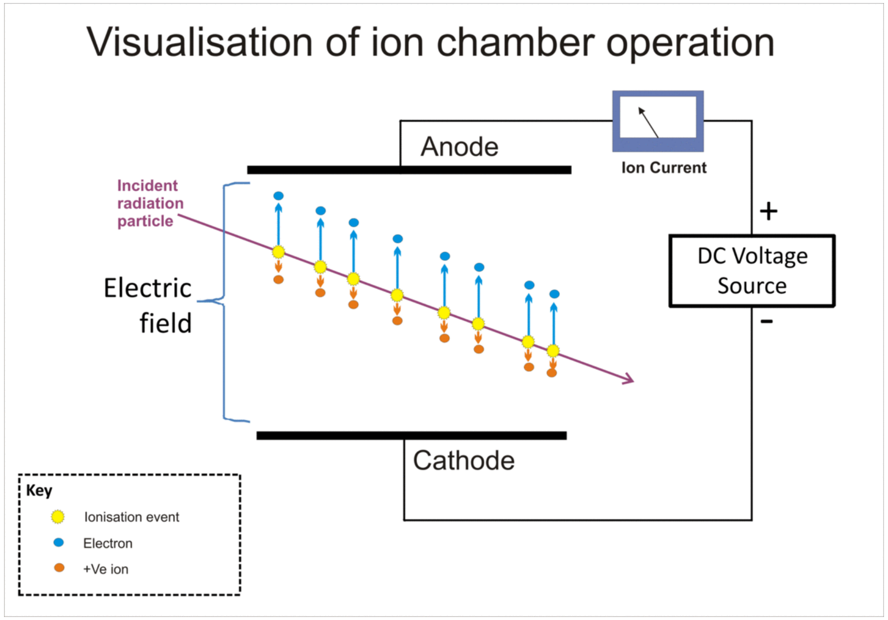




Gas-Filled Detectors

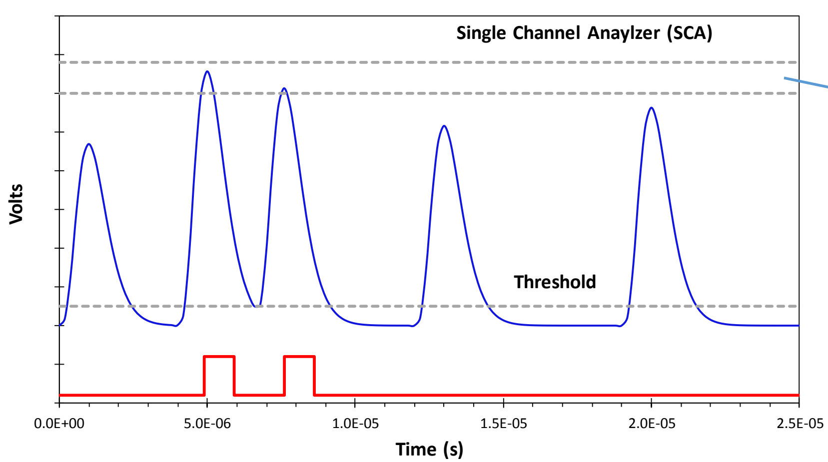
Ion chamber: Continuous or DC mode

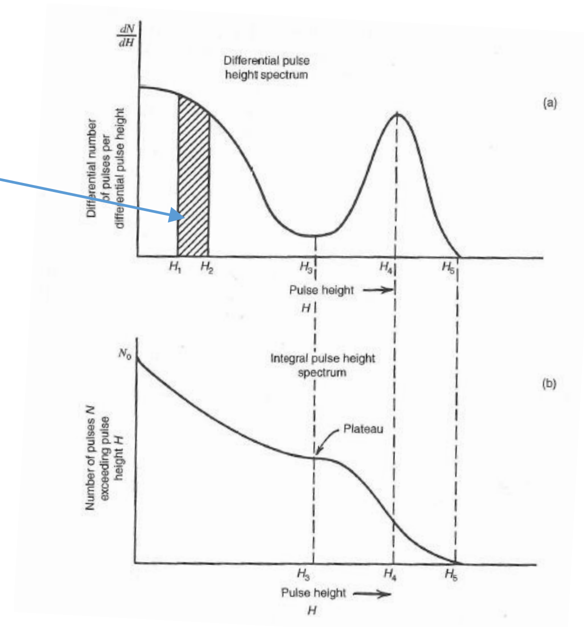
- *One can measure the continuous, average electric current*
- *This corresponds to the continuous, average dose rate*
- *Useful for radiation safety*
- *Tells you nothing about the type of radiation, the energy, the timing, etc*



Ion chamber: Pulse mode

- *One can measure properties of each discrete ionization event*
  - Total charge in each pulse → energy deposited by each particle
  - Can set thresholds → number or rate of events within energy ranges
  - Can measure distribution, or spectrum, of events
  - Can measure timing, many other properties
- *Most radiation measurements are pulse mode.*



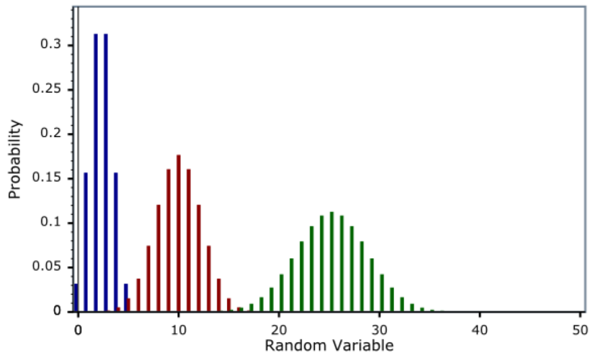


Radiation Measurements

- **Radiation measurements are unique**
  - *Some characteristics of radiation measurements are fundamentally different from the measurement of other physical quantities*
  - *These differences arise from the quantum nature*
- **Radiation is discrete, randomly timed quanta**
  - *If you measure temperature, you can measure it at some instant and with any time resolution you like*
  - *A radiation measurement is built of discrete quanta*
  - *At some instant, you may get no particle at all → <u>You MUST measure over some time duration</u>.*
  - *The precision of any measurement improves with the number of pulses*

Radiation Measurements

- **Counting statistics**
  - *Radioactive decay is a random process*
    - If average is 16 decays per second, get 16, 14, 17, 13, 18, 16, 19, …
  - *Any radiation measurement is subject to statistical fluctuation*
    - If you count N events, the standard deviation is $\sqrt{N}$
    - If $N=100$, $\sigma=10$ or 10%.
    - For $\sigma=1\%$, you need 10^4 counts
  - *Binomial distribution*

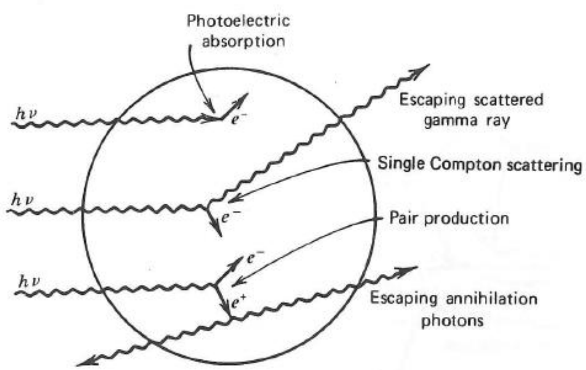


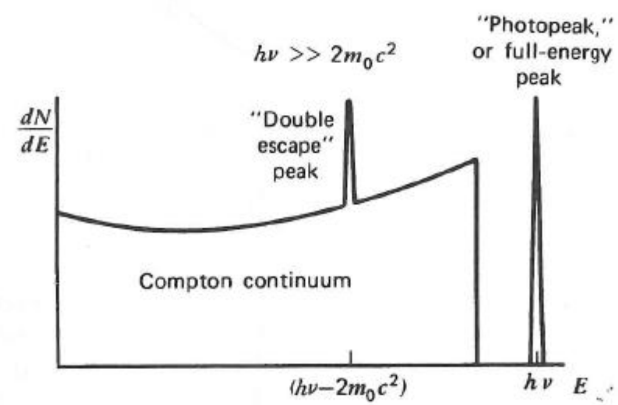
- **Critical and fundamental limit!**

Radiation Measurements

Intrinsic response function

- *Consider gamma-rays interacting in a detector*
    - Some pass through the detector → not detected (intrinsic efficiency <100%)
    - Some undergo photoabsorption → deposit full energy.
    - Some undergo Compton scatter; secondary photon exits detector → deposits only part of energy → continuum.
    - Some under pair production; photon exits → deposits sharp “escape peak”





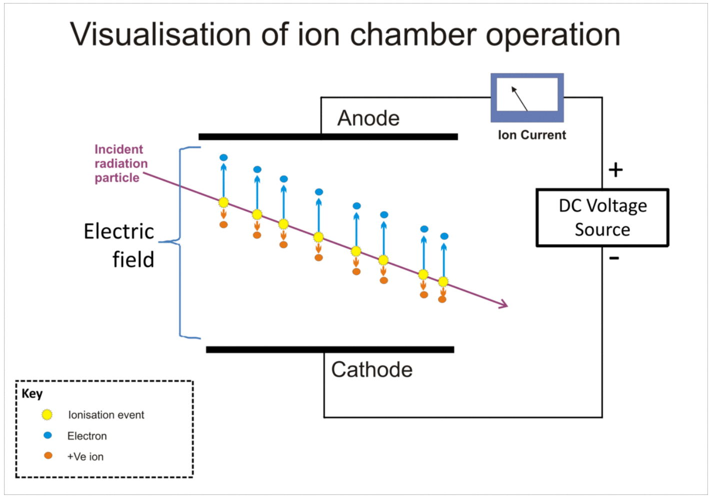
- *Physics of radiation interactions limit measurement*
    - We want to know the incident radiation field
    - Even a perfect sensor only measures the interaction outcomes

Radiation Measurements

- **Signals are really small & subject to fluctuations**
  - *Fluctuations in number of electron-ion pairs produced*
    - If 5 keV X-ray produces 200 electron-ion pairs, on average, expect $\sigma=\sqrt{200}=14$
    - Actually smaller than this
  - *"DC" currents arise from discrete electrons → random fluctuations*
    - If N electrons pass into transistor, $\sigma=\sqrt{N}$
    - Random current fluctuations mask small current pulses
  - *Induced currents from EMI, power supply ripple, etc*
    - Signal current is picoamps → induced stray currents must be much smaller.

4. Radiation Detectors

Planar ion chamber



- *Signal Current*
  - Charge velocity $$v = \left(\frac{\mu}{P}\right)\left(\frac{V}{L}\right)$$
  - Electrons typical 1000 m/s, so 100 μs to cross 1 cm

    5 MeV α → 300 pA *5 keV X-ray → 300 fA*
  - Ions typical 1 m/s, so 0.1 second to cross 1 cm
  - Pulses are VERY long, too long to get millions of counts
    - Recombination occurs → Signal deficit
    - Pulse duration and shape depend on details of particle track

Gas-Filled Detectors

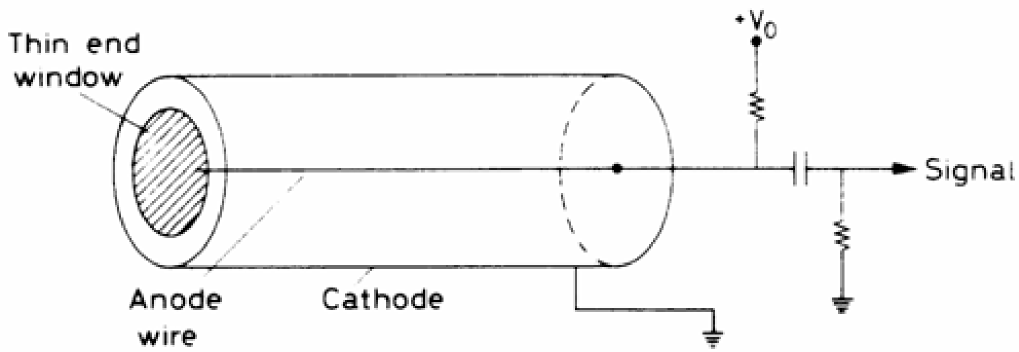
Cylindrical ion chamber

- *Concept*
  - Electric field much stronger near wire

$$E = \frac{V}{r \ln\left(R_o / R_i\right)}$$

  - Electron speed (and thus current) peaks as electrons near wire
  - Leads to a much shorter pulse, submicrosecond

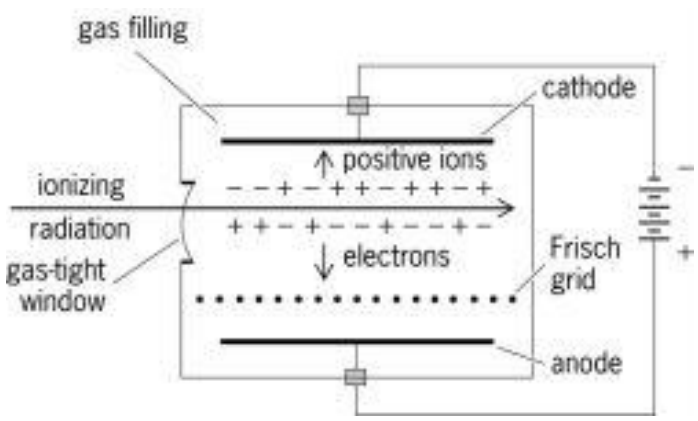
- *Key principles*
  - Signal current arises when charge MOVE not when COLLECTED
  - Electrode design can greatly impact signal characteristics



Gas-Filled Detectors

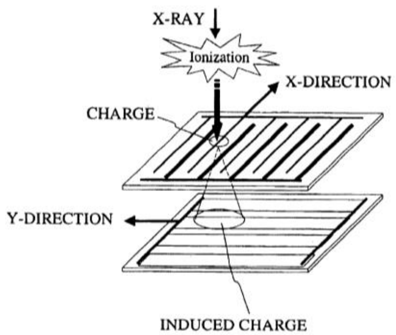
Frisch Grid

- *Measure current between grid and anode*
- *Signal arises only from electrons*
- *Pulse duration is much shorter, due to smaller path and electron speed*
- *Pulse shape is fixed, because path length is always the same*

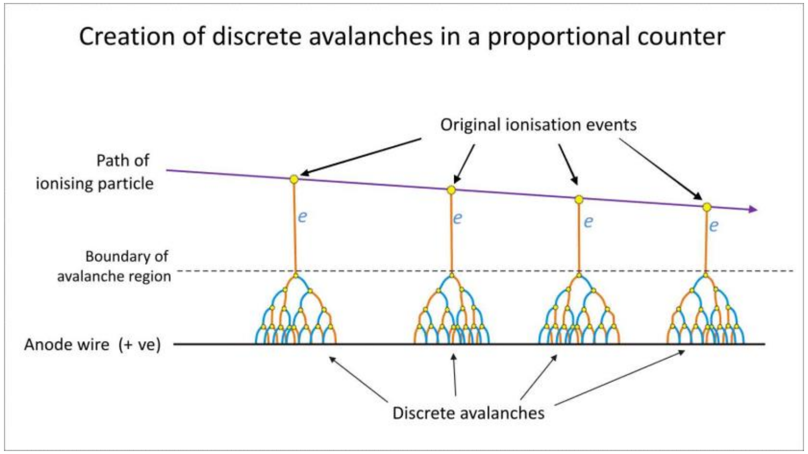


Wire chamber

- *Measure current collected on two orthogonal grids*
- *Gives position information*
- *Widely used in high energy physics*



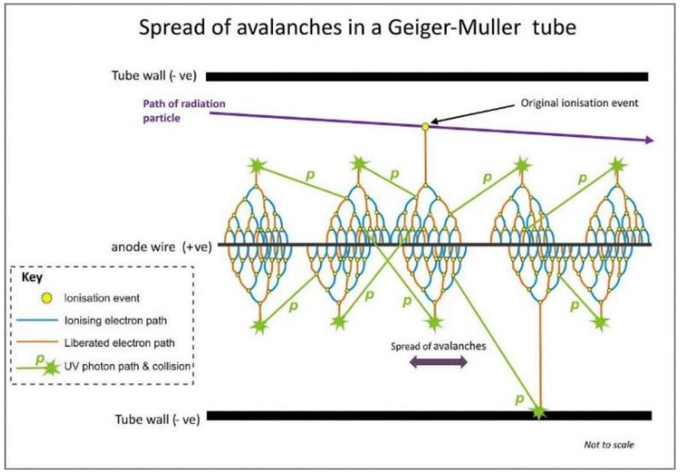
Proportional Counter



- *Concept*
  - Cylindrical chamber but with a higher bias
  - Electrons eventually reach velocity high enough to knock electrons off atoms
  - Leads to "avalanche gain": Each electron initially produced, gives 2 or 5 or 10
  - Output current is proportional to input
- *Advantage: Bigger signal to simplify electronics*
- *Disadvantages*
  - Get extra fluctuations from avalanche process
  - Output depends strongly on voltage, temperature, etc.

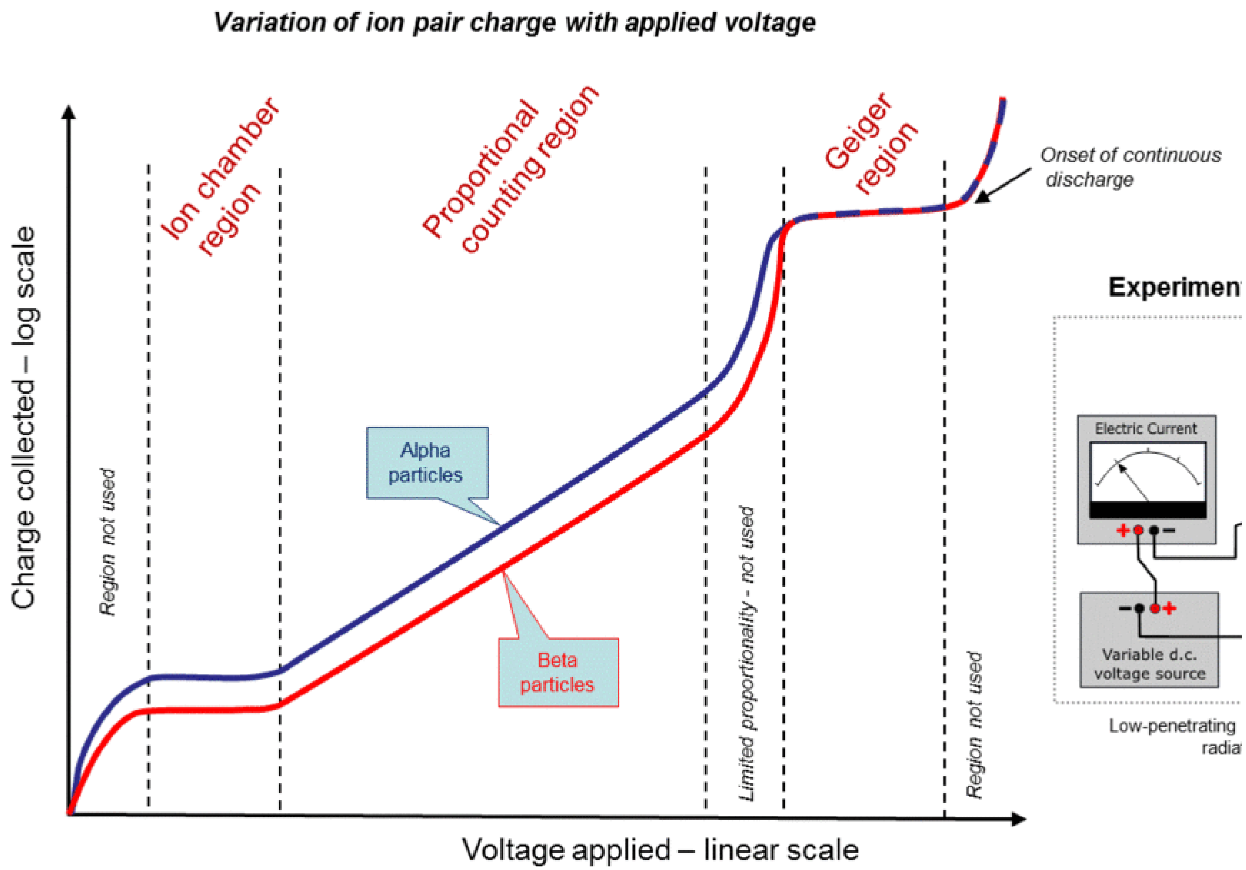
Gas-Filled Detectors

Geiger Counter

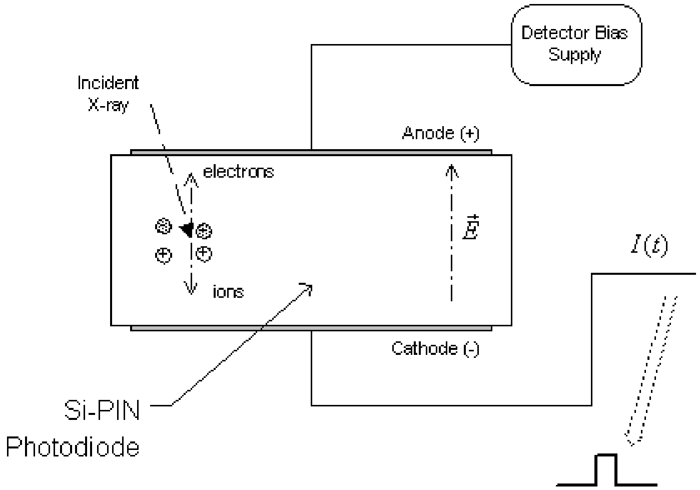


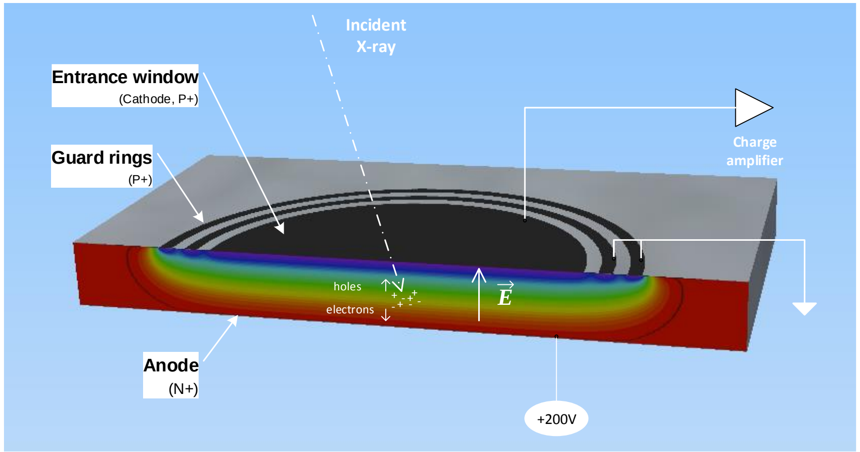
- *Concept*
  - Like prop counter but field is even higher
  - Ions also accelerate enough to create avalanche, more electrons, etc
  - Creates so much charge, it pulls down HV bias (discharges capacitor)
- *Results*
  - All initial events, from smallest to one electron, give same size big output
  - Very sensitive, to even smallest signals
  - Only for counting. No information on energy, type of particle, etc.

Gas-Filled Detectors



Planar semiconductor detector





- *Concept*
  - Basically a solid state version of gas detector
  - Reverse biased PN junction gives "depletion region" with no free charges
  - Ionizing particle creates charge, which is swept by electric field
- *Advantages*
  - Less energy to create a pair → bigger signal, less intrinsic fluctuation
  - Higher density and atomic number for better stopping

Detectors

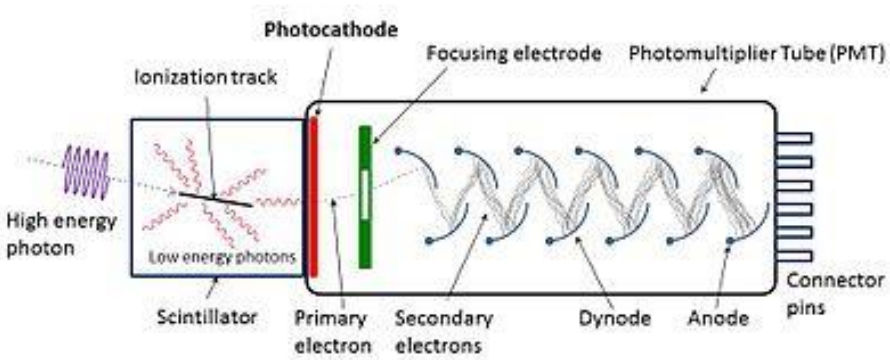
Semiconductor detectors

- *Cylindrical geometry*
  - Like cylindrical gas chamber
  - Give better electric field to avoid breakdown
  - Common in high purity germanium for gamma-ray spectroscopy
- *Frisch grid*
  - One cannot fabricate a grid inside a semiconductors
  - Properly patterned surface electrodes give similar results
- *Avalanche diodes*
  - Like a proportional counter
  - High field region near PN junction gives avalanche gain
- *Geiger mode*
  - Avalanche diode can be operated in Geiger mode

Detectors

Scintillation detector

- *Interaction produces excited state in crystal*
  - E_i is high (light yield low) → photosignal is small and F = 1
  - Pulse duration varies widely: from <nanosec to microseconds
- *Photons interact in a photodetector*
  - Photodiodes are used but signal current is small
  - Photomultiplier with high gain (~10^5) common
- *Advantages*
  - Optically clear crystals can be grown very large
  - Many materials → Wide range of properties (density, speed, resolution, …)
  - With a PMT, the signal is quite large



Detectors

Gas filled

- *Why would we use gas detectors?*
  - Inexpensive per unit volume: you can make them huge
  - You can adjust the gas mixture and density to optimize for measurements
  - You can easily get multiplication for larger signals
- *Types: DC Ionization, proportional, Geiger, wire chambers*

Semiconductors

- *Why would we use semiconductors?*
  - Much larger signals (more charge) → better signal to noise ratio
  - Higher density → Can stop radiation in a much smaller volume
  - Semiconductor processing is very sophisticated
- *Types: Si photodiode, HPGe, Si drift detector, Si avalanche photodiode, CdTe, …*

Scintillators

- *Why would we use scintillators?*
  - Inexpensive per unit volume: can make them large, with better density than gas
  - With a PMT, very large signal
- *Types: PMT vs photodiode, many materials (NaI(Tl), BGO, etc)*