Chemical Engineering 412

Introductory Nuclear Engineering

Lecture 17

Radiation Detection & Measurement

Spiritual Thought

"My message to you today is to 'fear not, little flock.' It is to encourage you to rejoice in the great blessings of life. It is to invite you to feel the great thrill of gospel living and our Father in Heaven's love. Life is wonderful, even in the hard times, and there is happiness, joy, and peace at stops all along the way, and endless portions of them at the end of the road."

Howard W. Hunter

Objectives

- Know the principles behind detecting radiation
- Know detectors' performance metrics:
  - deadtime, radiation type, energies, operation modes, paralyzablility, efficiency, etc.
- Understand the influence of voltage and design on detection
- Be prepared to build your own detector!

Radiation


INVOLVING OUR MILITARY PERSONNEL
in the development of the Atomic Bomb
SECTION 1.6 - RADIATION
15

Detector Types

- Gas-filled – Gas between two electrodes
- Scintillation – Ionizing radiation produces UV or visible light
- Solid-state, Semiconductor – High purity Si or Ge semiconductors
- Others
  - Cloud chambers
  - Bubble Chambers
  - Superheated Drop
  - Cryogenic
  - AMANDA and IceCube

Cloud Chamber

Detector Parameters

- Detection Mode
- Operation Mode
- Dead Time / Interaction Rate
- Paralyzable / Non-Paralyzable
- Efficiency

Detector Operation

- Detection mode – i.e. how they work
  - Counters – detect number of interaction events
  - Spectrometers – detect number of events as a function of energy
  - Dosimeters – detect accumulated energy by all interactions
- Operation mode – i.e. how they tell us
  - Pulse – detects (and generally counts) individual interactions
  - Current –individual interactions averaged to produce current

Dead time

- Maximum rate at which data can be recorded
  - Limited by dead time, τ
  - Unable to record more counts

    n = true count rate

    m = recorded count rate

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

- Duty cycle of slowest component determines dead time
  - Longest dead time
    - Geiger-Müller (GM) counting
    - In multichannel analyzer systems - analog-to-digital converter
- GM counters dead times ~ 10 – 100 ms
  - most other systems < 3-8 ms

Interaction rate

- In pulse mode, events must be separated by more than the dead time to be detected
- A second interaction in this interval will not be detected
- A second interaction very close to the first interaction may distort the signal from the first interaction

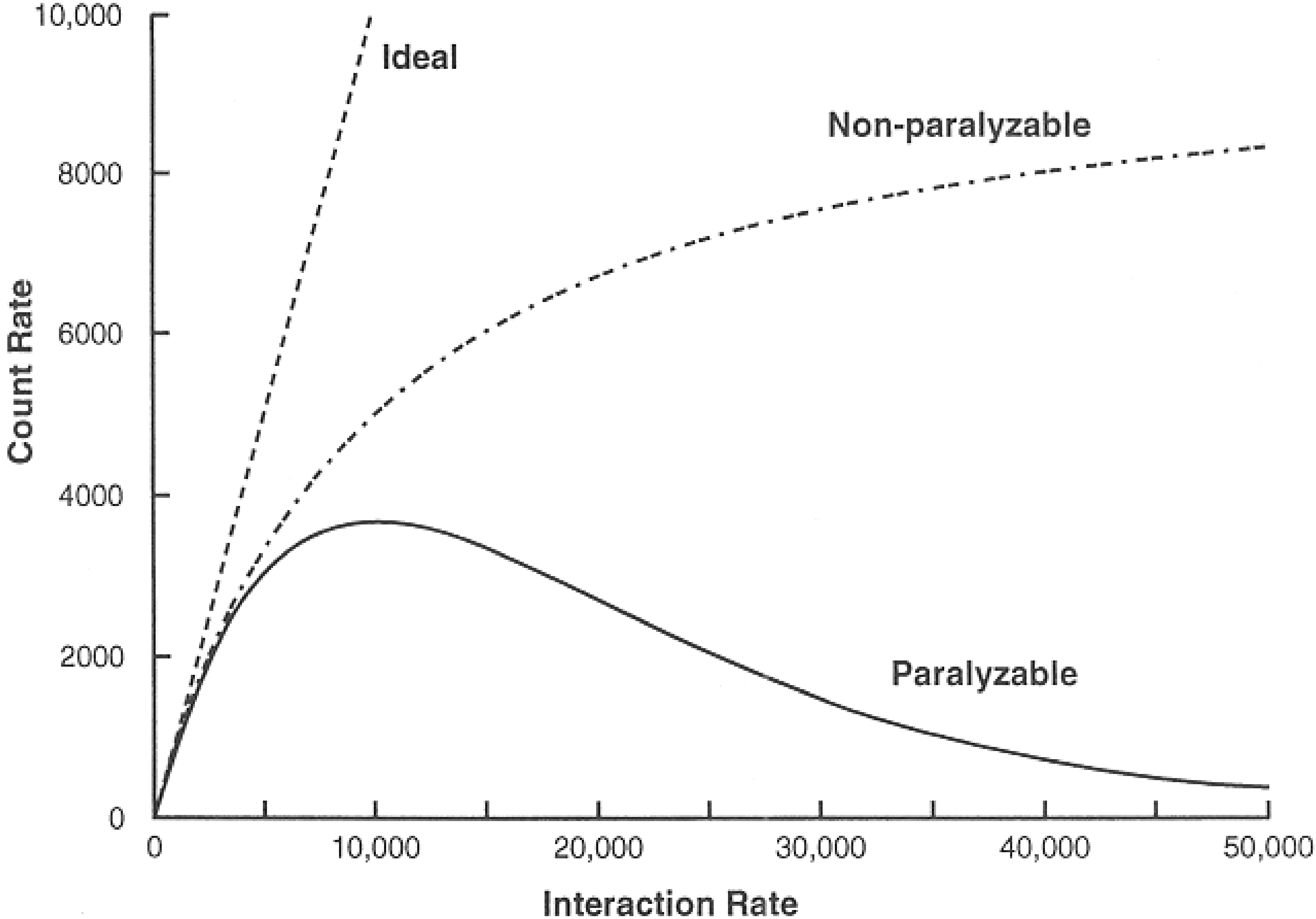
Example

- The year is 2278, and you are the sole survivor of a nuclear holocaust. As you exit the bunker to explore the surrounding wasteland, you notice that your trusty Pip-boy indicates that a count rate of 300 counts/s will turn you into a scavenging, raging zombie creature. With this in mind, you equip a GM counter, which has a deadtime of 100μ, indicates a count rate of 290 counts/s. Are you doomed to join the zombie scavengers?

Paralyzable or nonparalyzable

- Systems in which dead-time events extend dead time are *paralyzable*. Otherwise, systems are *nonparalyzable.*
- At very high interaction rates, paralyzable systems will not detect any interactions after the first, causing the detector to indicate a count rate of zero

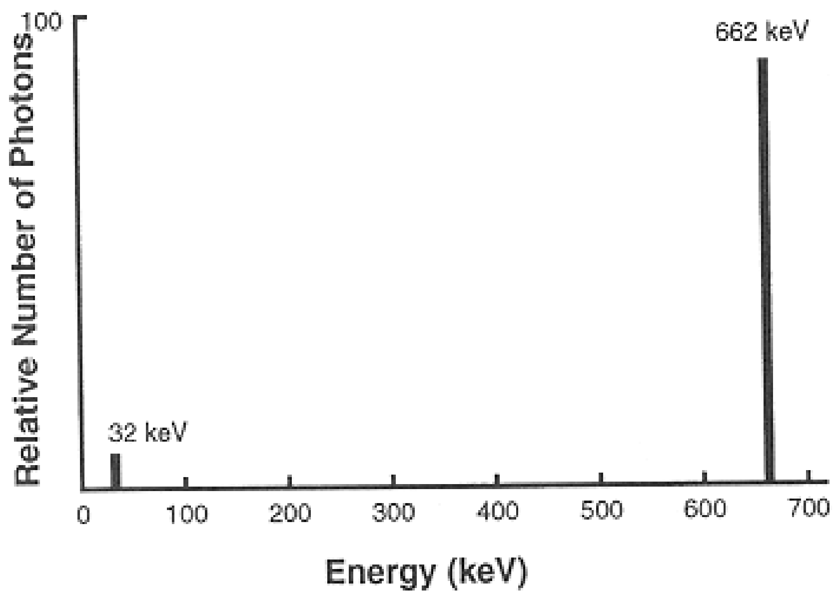
Counter performance

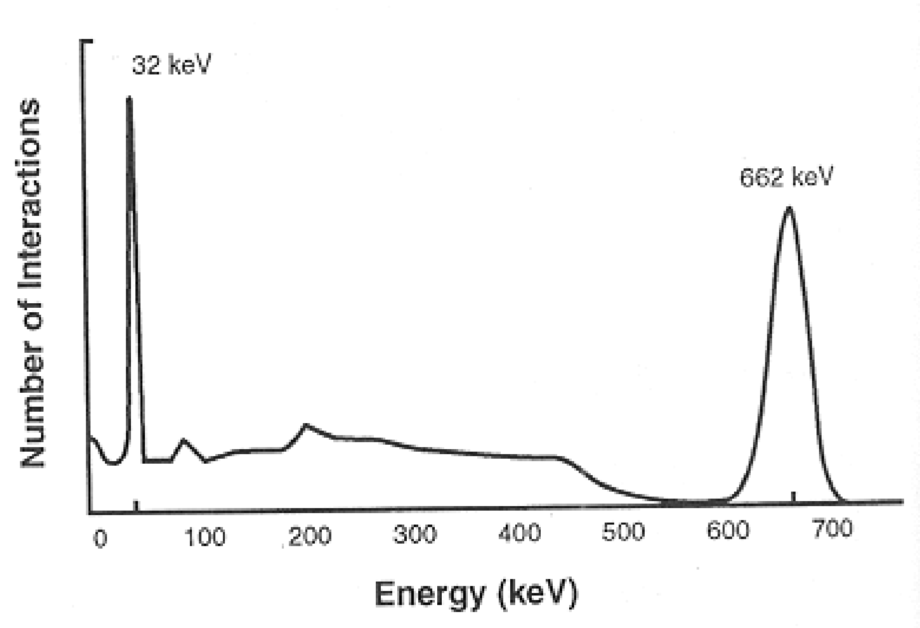


Spectroscopy (Like O-Chem!)

- Most spectrometers operate in pulse mode
- Amplitude of each pulse is proportional to the energy deposited in the detector by the interaction causing that pulse
- *The energy deposited by an interaction is not always the total energy of the incident particle or photon*
- *Pulse height spectrum* - graph of the number of interactions depositing a particular amount of energy as a function of energy

Pulse Detector Examples





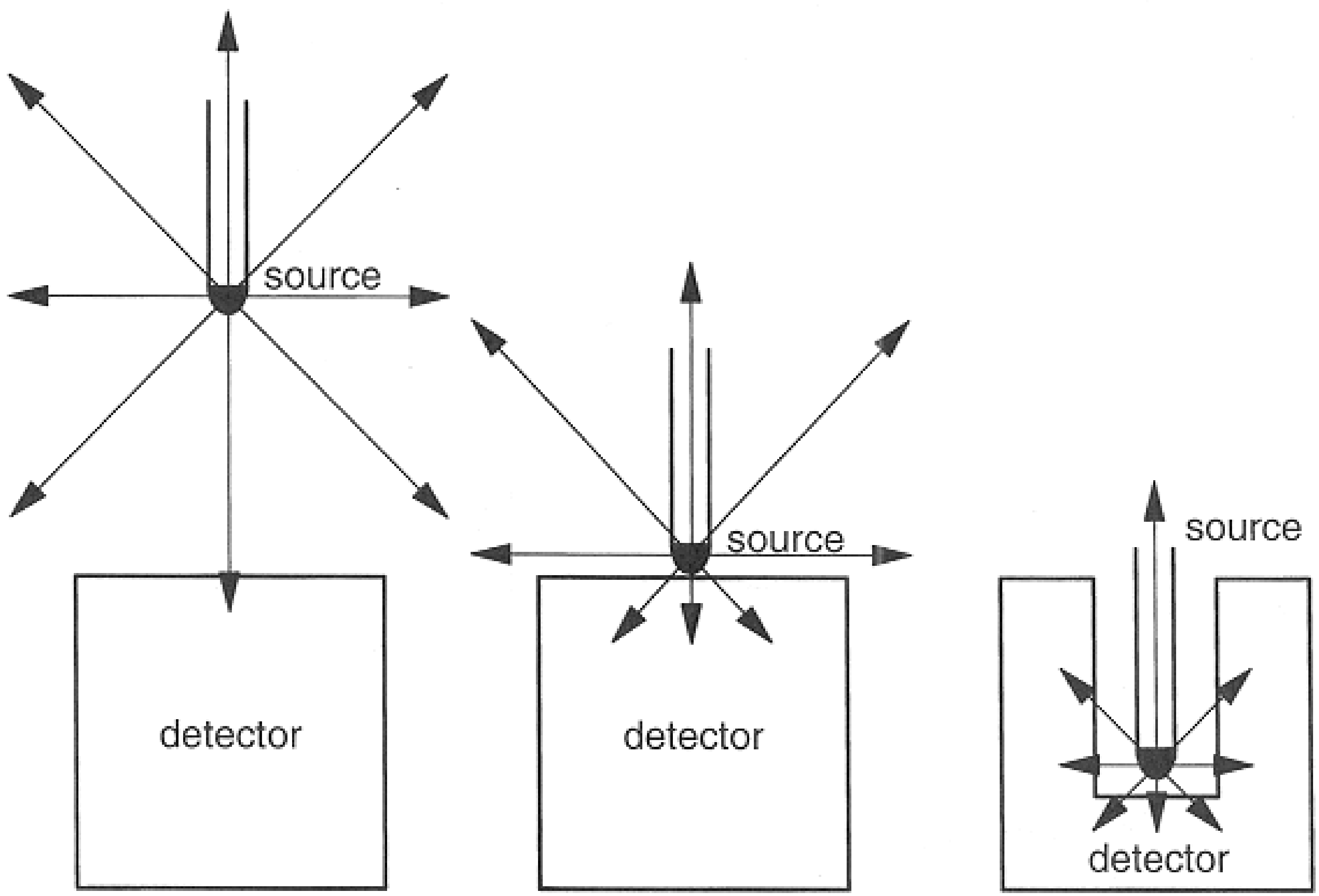
Current mode operation

- In current mode, all information regarding individual interactions is lost, but these systems can be designed with no dead time
- If the electrical charge collected from each interaction is proportional to the energy deposited by that interaction, then the net current is proportional to the dose rate in the detector material
- Used for detectors subjected to very high interaction rates

Detection efficiency

- The *efficiency (sensitivity)* of a detector is a measure of its ability to detect radiation
- Efficiency of a detection system operated in pulse mode is defined as the probability that a particle or photon emitted by a source will be detected

Efficiency Illustrations



Efficiencies

$$\eta_{overall} \equiv \frac{\#_{detected}}{\#_{emitted}}$$

$$\eta_{geom} \equiv \frac{\#_{reaching\ detector}}{\#_{emitted}}$$

$$\eta_{intrinsic} \equiv \frac{\#_{detected}}{\#_{reaching\ detector}}$$

$$\eta_{overall} = \eta_{geom}\eta_{intrinsic}$$

Intrinsic efficiency

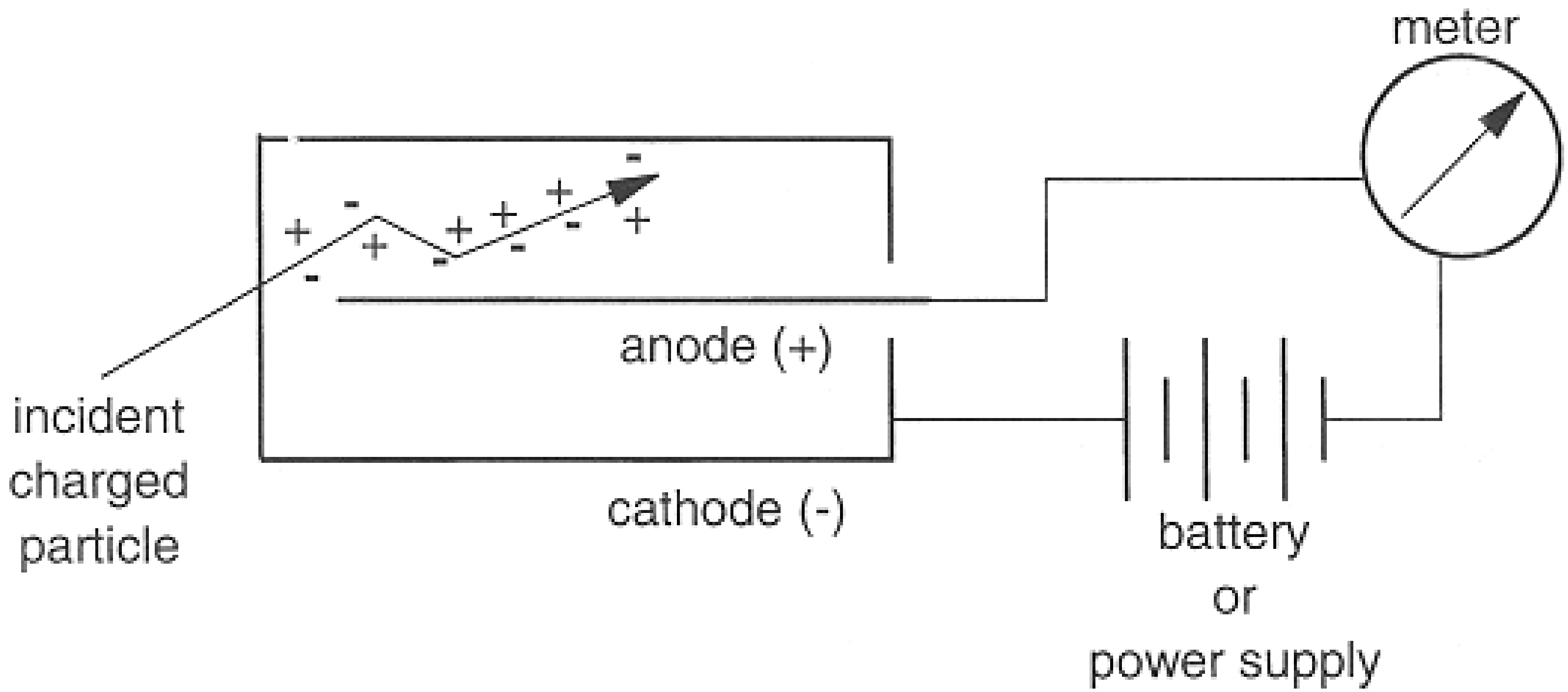
- Often called the *quantum detection efficiency* or QDE
- Determined by the energy of the photons and the atomic number, density, and thickness of the detector
- For a parallel beam of monoenergetic photons incident on a detector of uniform thickness:

$$\eta_{intrinsic} = 1 - \mathrm{e}^{-\mu x}$$

Gas-filled detectors

- A gas-filled detector comprises gas between two oppositely charged electrodes
- Ionizing radiation produces ion pairs in the gas
- Positive ions (cations) migrate to negative electrode (cathode); electrons or anions migrate to positive electrode (anode)
- In most detectors, cathode is the wall of the container that holds the gas and anode is a wire inside the container

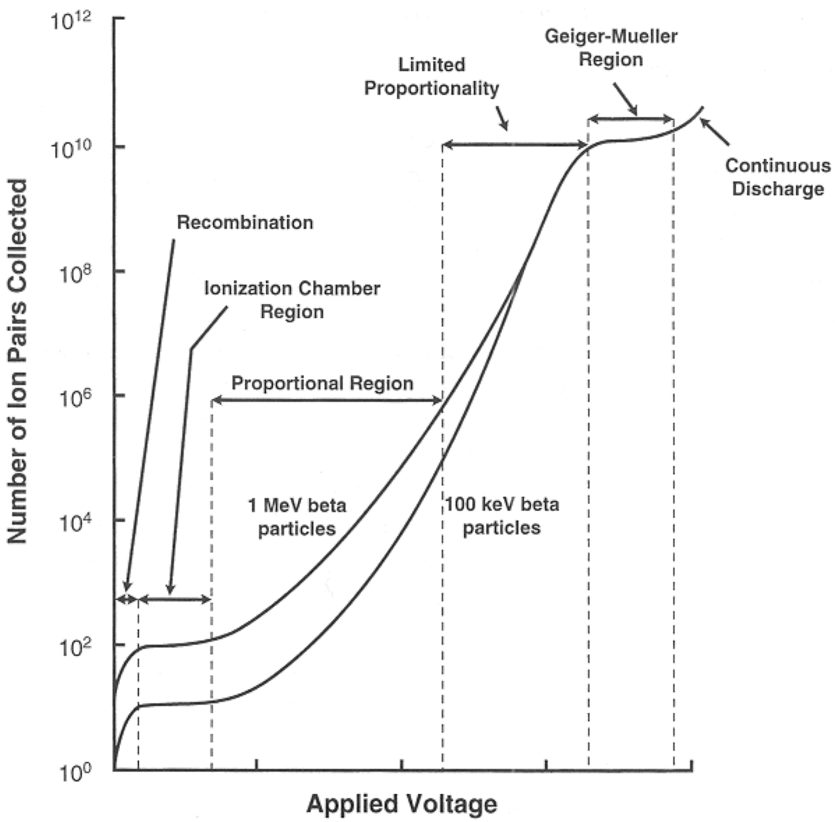
Typical gas-filled detector

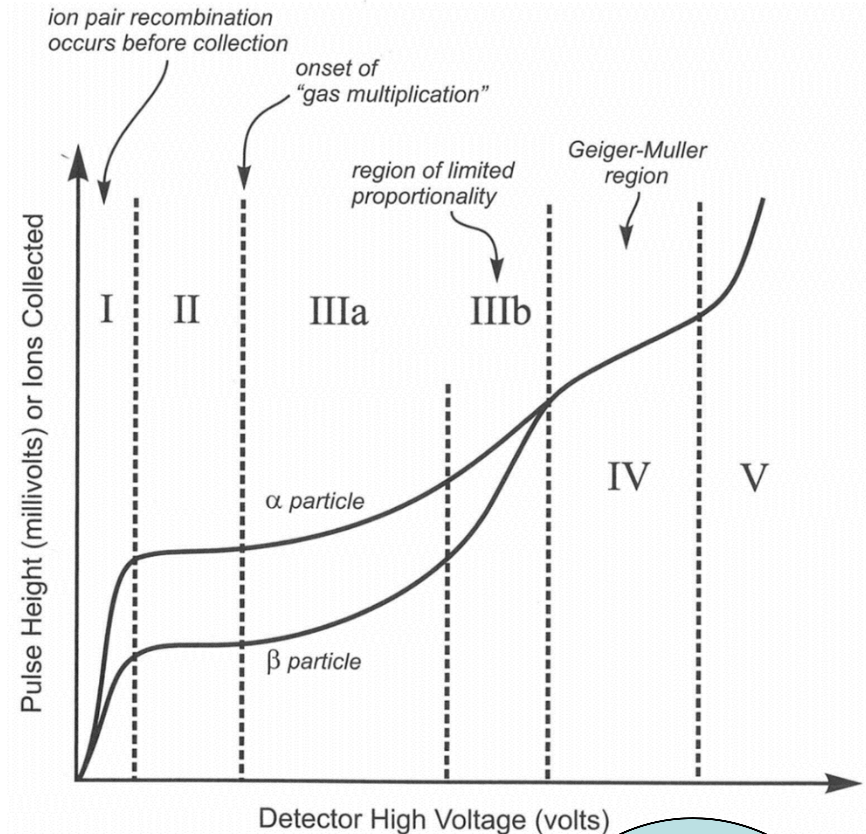


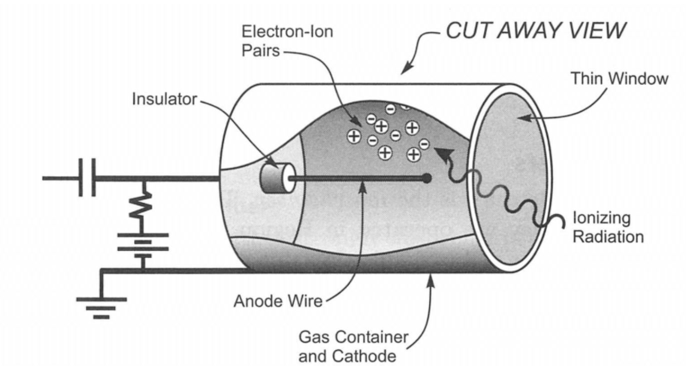
Types of gas-filled detectors

- Three types of gas-filled detectors in common use:
  - Ionization chambers
  - Proportional counters
  - Geiger-Müller (GM) counters
- Type determined primarily by the voltage applied between the two electrodes
- Ionization chambers have wider range of physical shape (parallel plates, concentric cylinders, etc.)
- Proportional counters and GM counters must have thin wire anode (why)

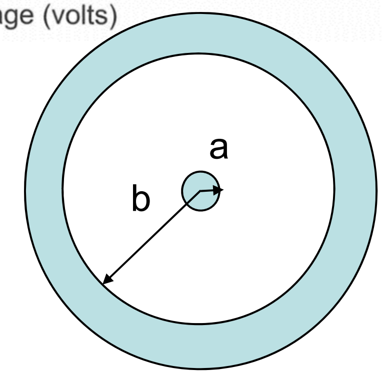
Voltage influence on Sensitivity







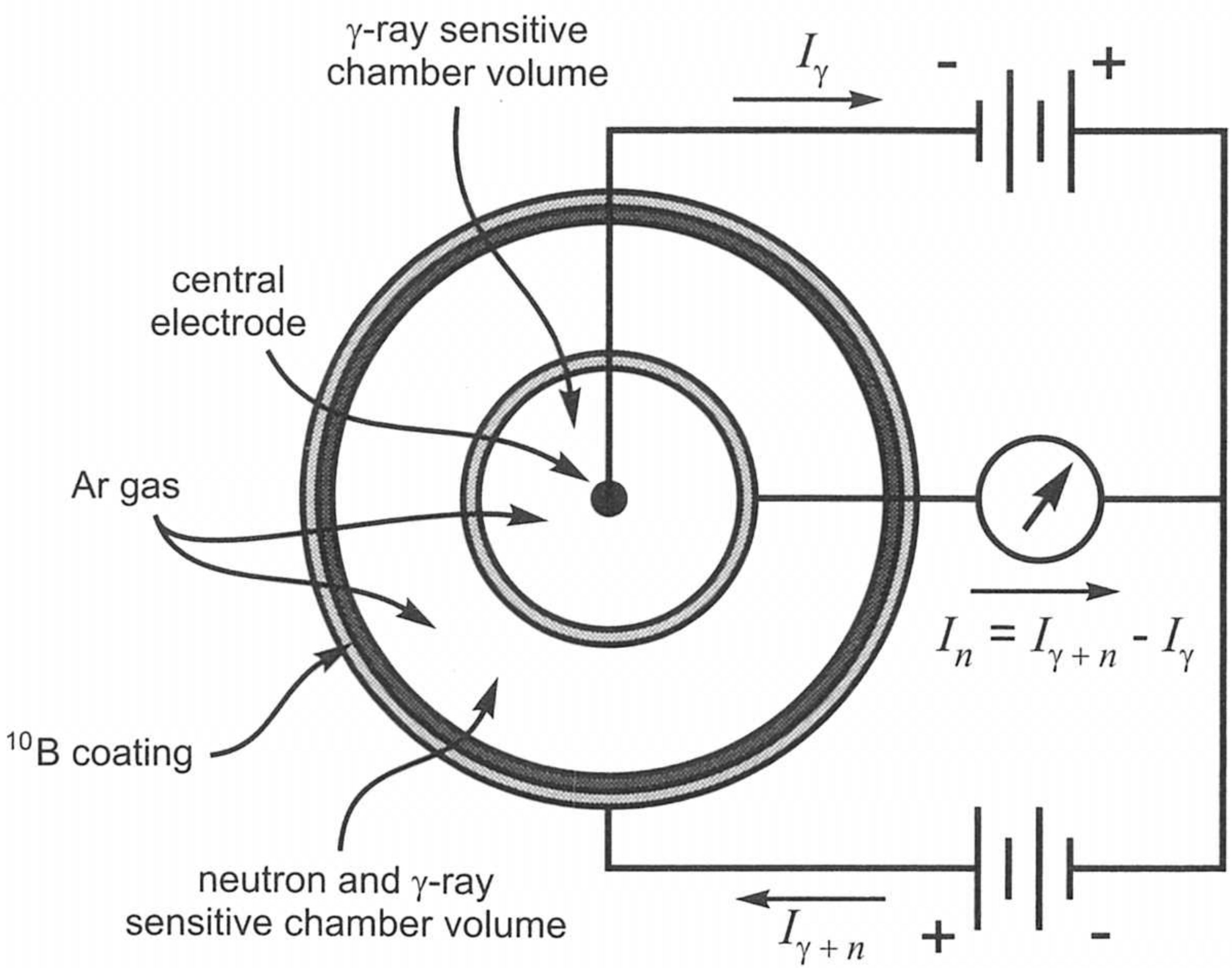
$$E = \frac{V_o}{r \cdot \ln(b/a)}$$



Ionization chambers

- If gas is air and walls of chamber are of a material whose effective atomic number is similar to air, the amount of current produced is proportional to the exposure rate
- Air-filled ion chambers are used in portable survey meters, for performing QA testing of diagnostic and therapeutic x-ray machines, and are the detectors in most x-ray machine phototimers
- Low intrinsic efficiencies because of low densities of gases and low atomic numbers of most gases

Compensated Ion Chamber

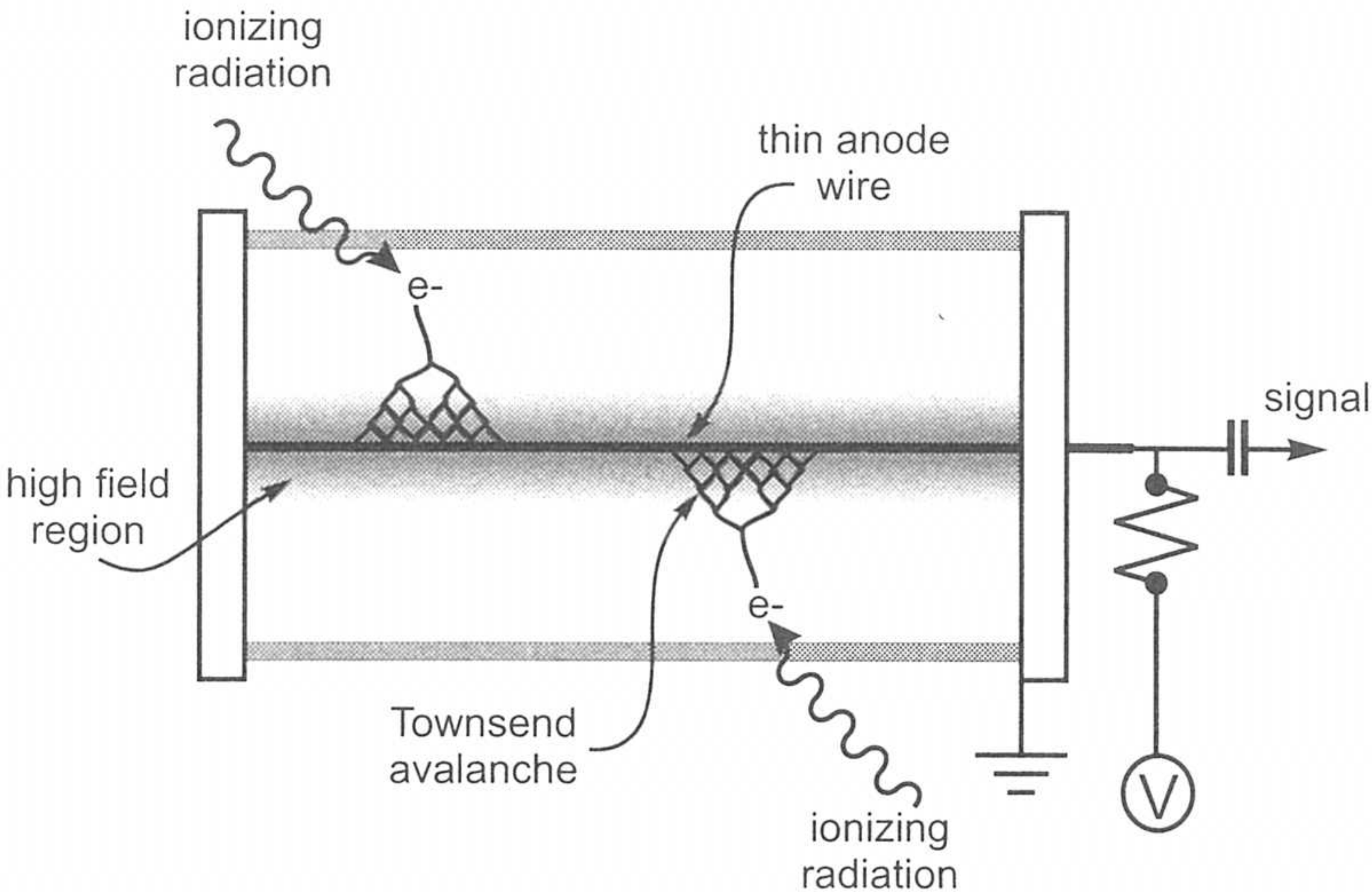


Ionization Chambers

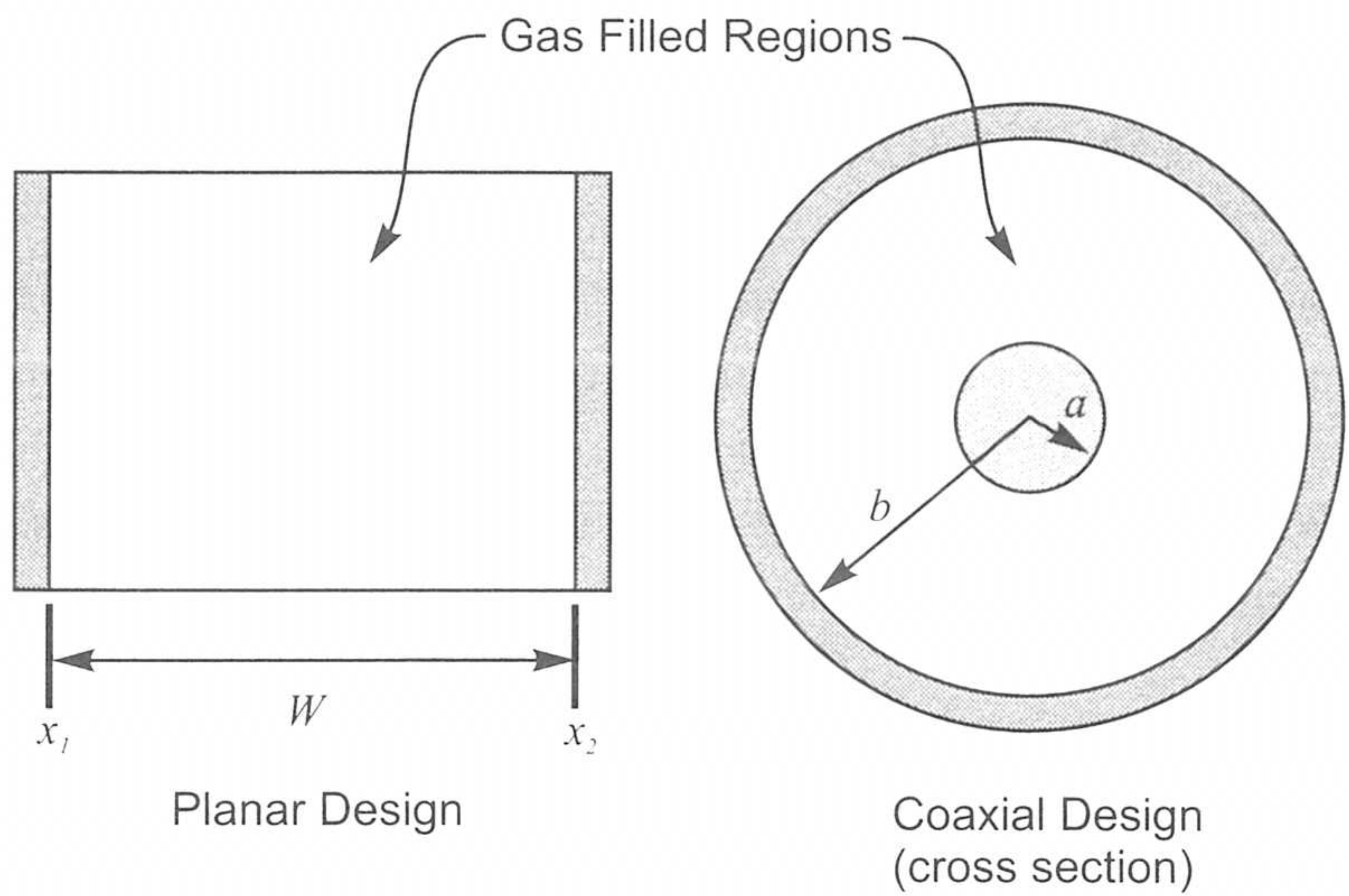
Proportional counters

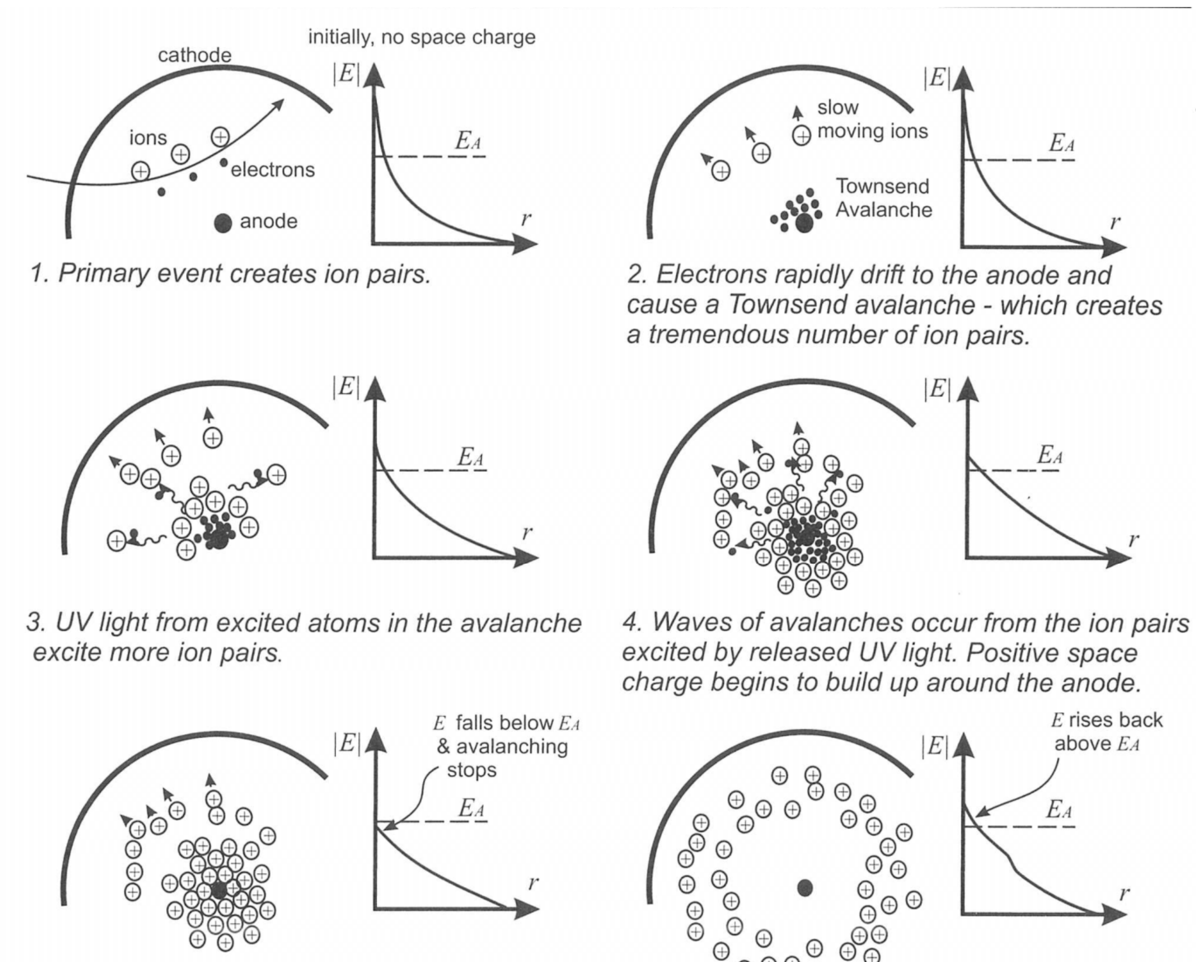
- Must contain a gas with specific properties
- Commonly used in standards laboratories, health physics laboratories, and for physics research
- Seldom used in medical centers

Proportional Counter



Proportional Counter





1. Primary event creates ion pairs.

2. Electrons rapidly drift to the anode and cause a Townsend avalanche - which creates a tremendous number of ion pairs.

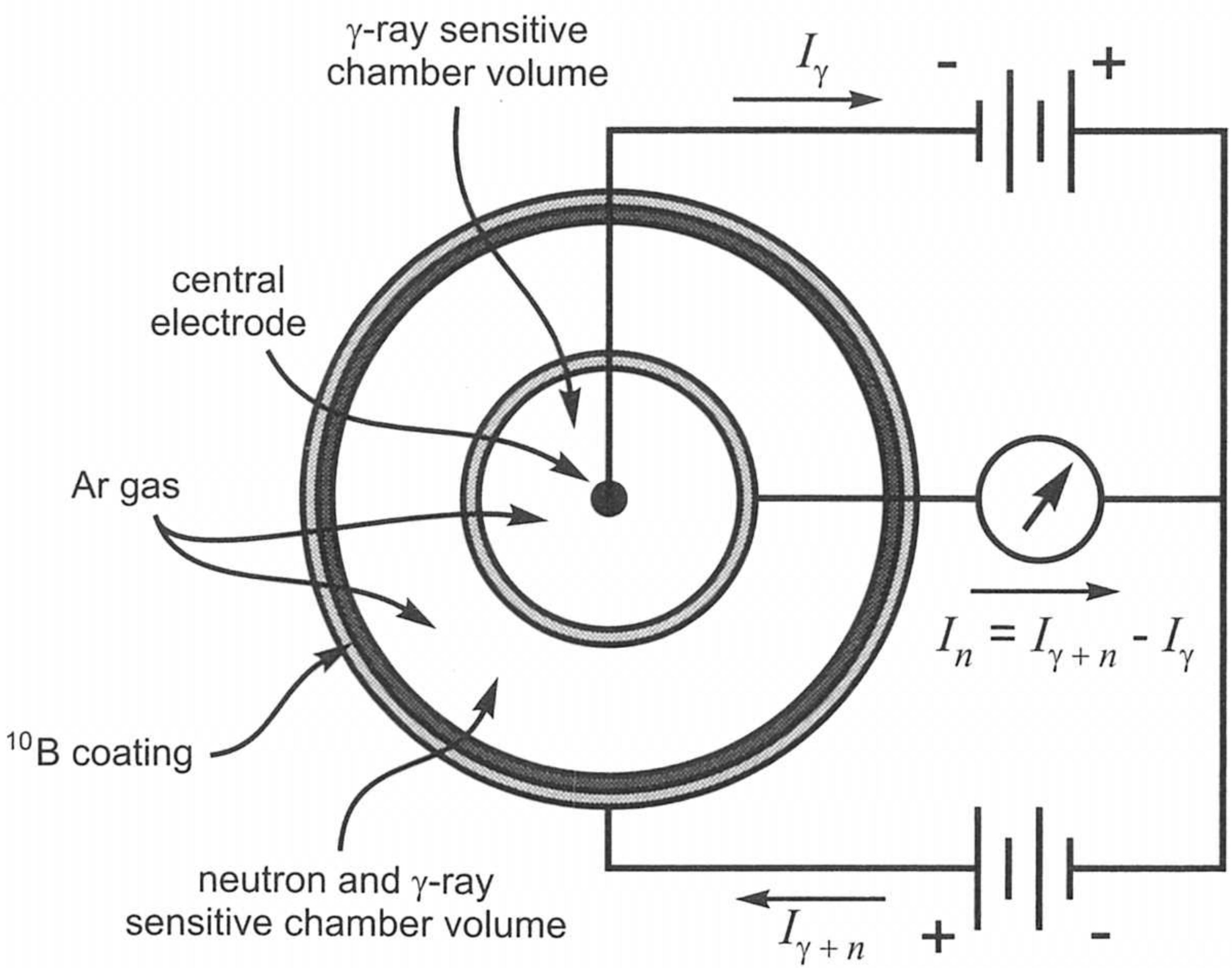
3. UV light from excited atoms in the avalanche excite more ion pairs.

4. Waves of avalanches occur from the ion pairs excited by released UV light. Positive space charge begins to build up around the anode.

5. Positive space charge builds up around the anode to the point that the electric field is reduced below the critical value for avalanching. The avalanching ceases.

6. The space charge drifts away from the anode towards the cathode (wall). The electric field recovers such that another Geiger discharge can occur.

Compensated Ion Chamber



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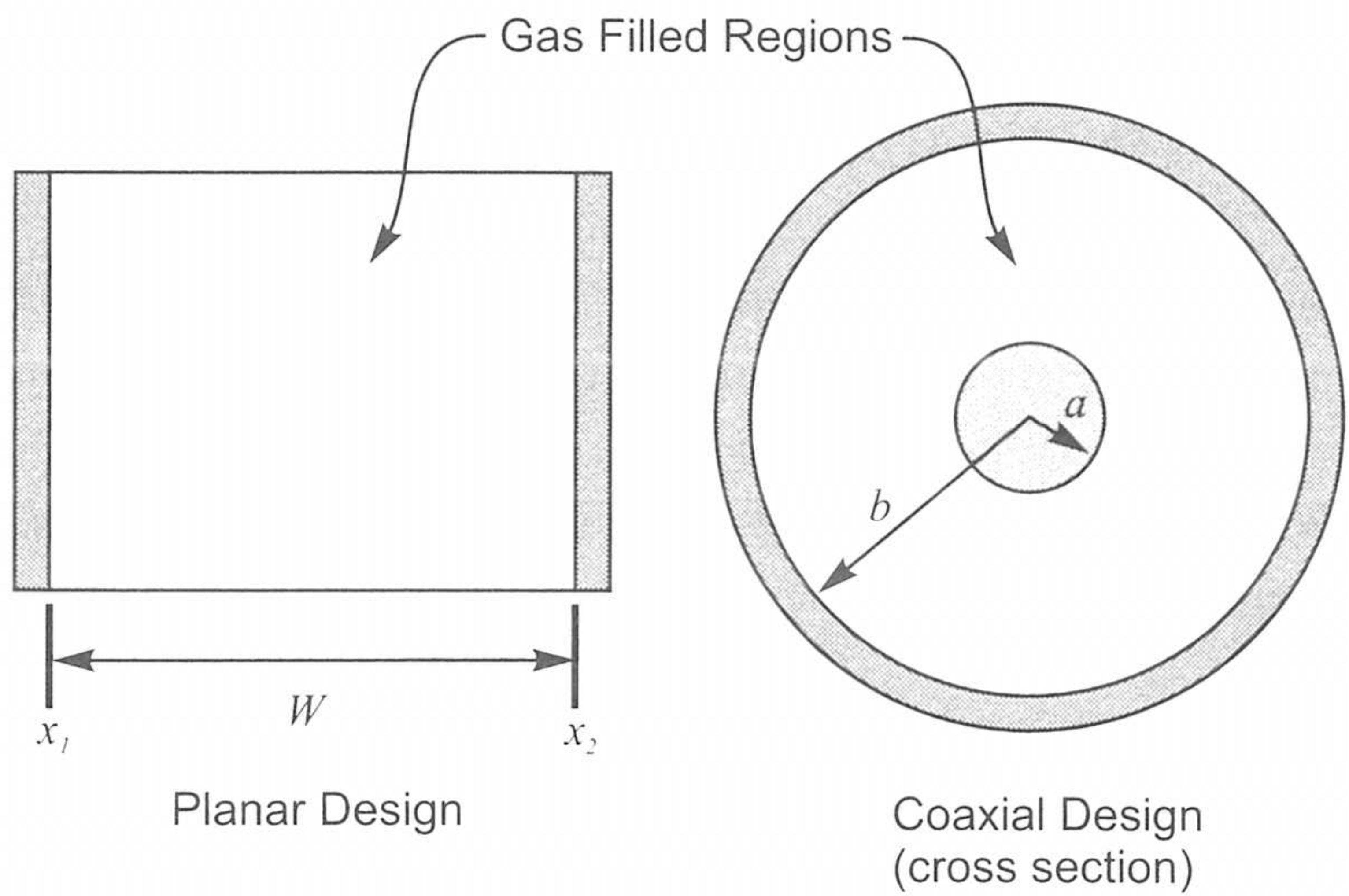
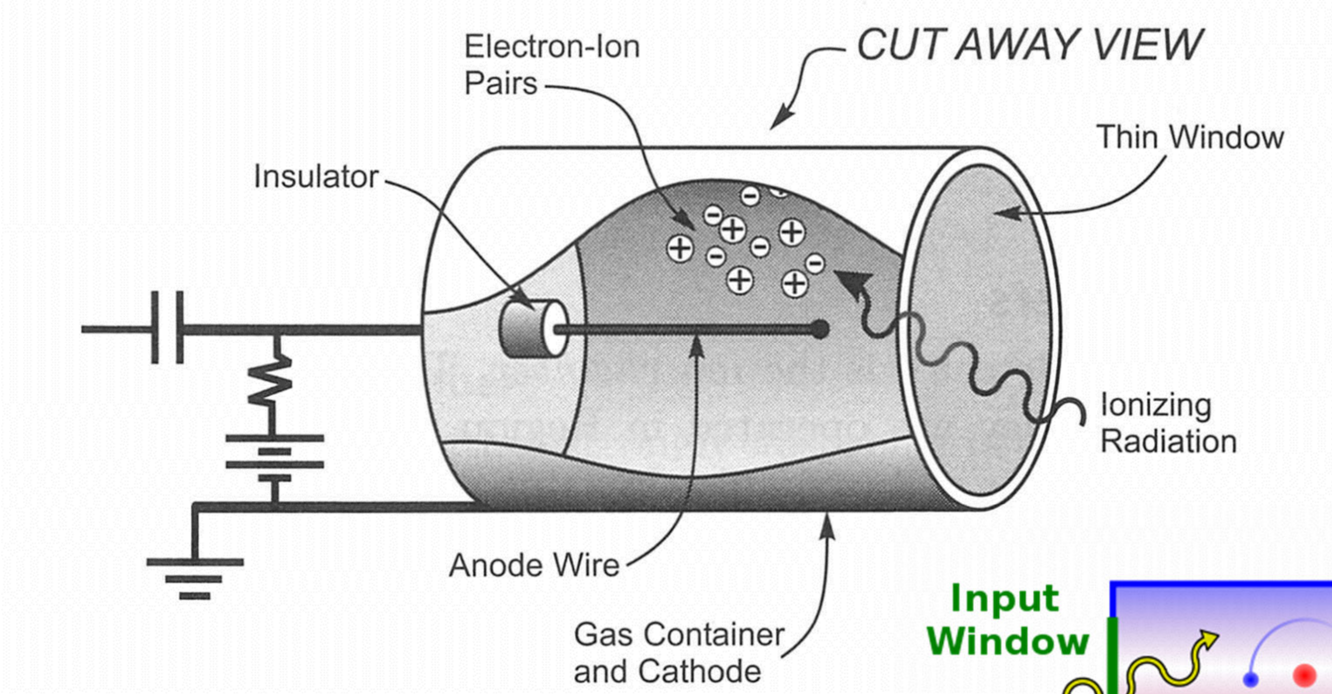


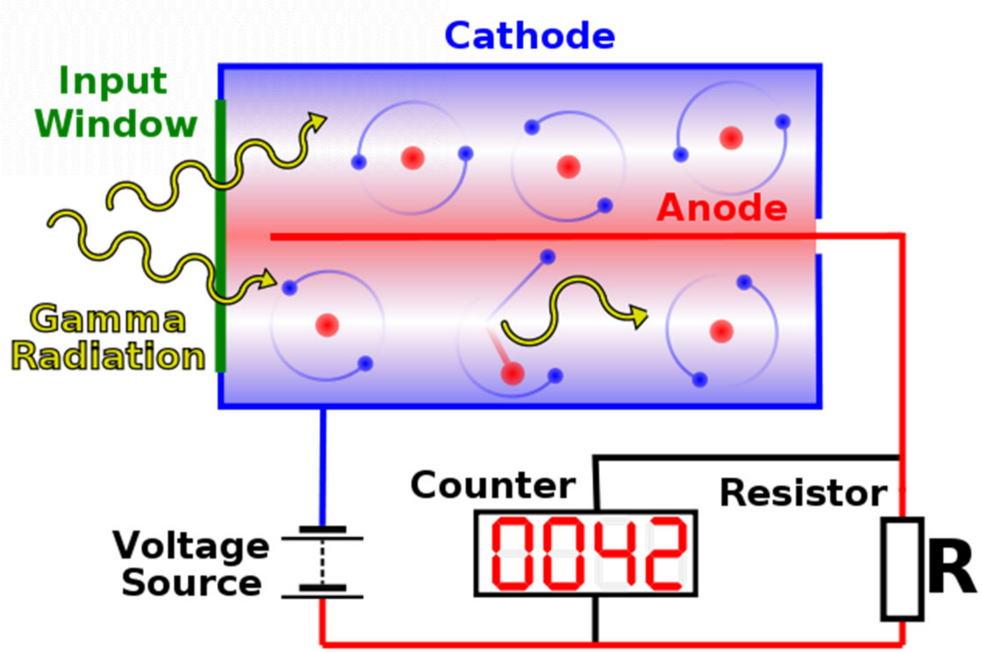
GM counters

- GM counters also must contain gases with specific properties
- Gas amplification produces billions of ion pairs after an interaction – signal from detector requires little amplification
- Often used for inexpensive survey meters
- In general, GM survey meters are inefficient detectors of x-rays and gamma rays
- Over-response to low energy x-rays – partially corrected by placing a thin layer of higher atomic number material around the detector

GM Counter

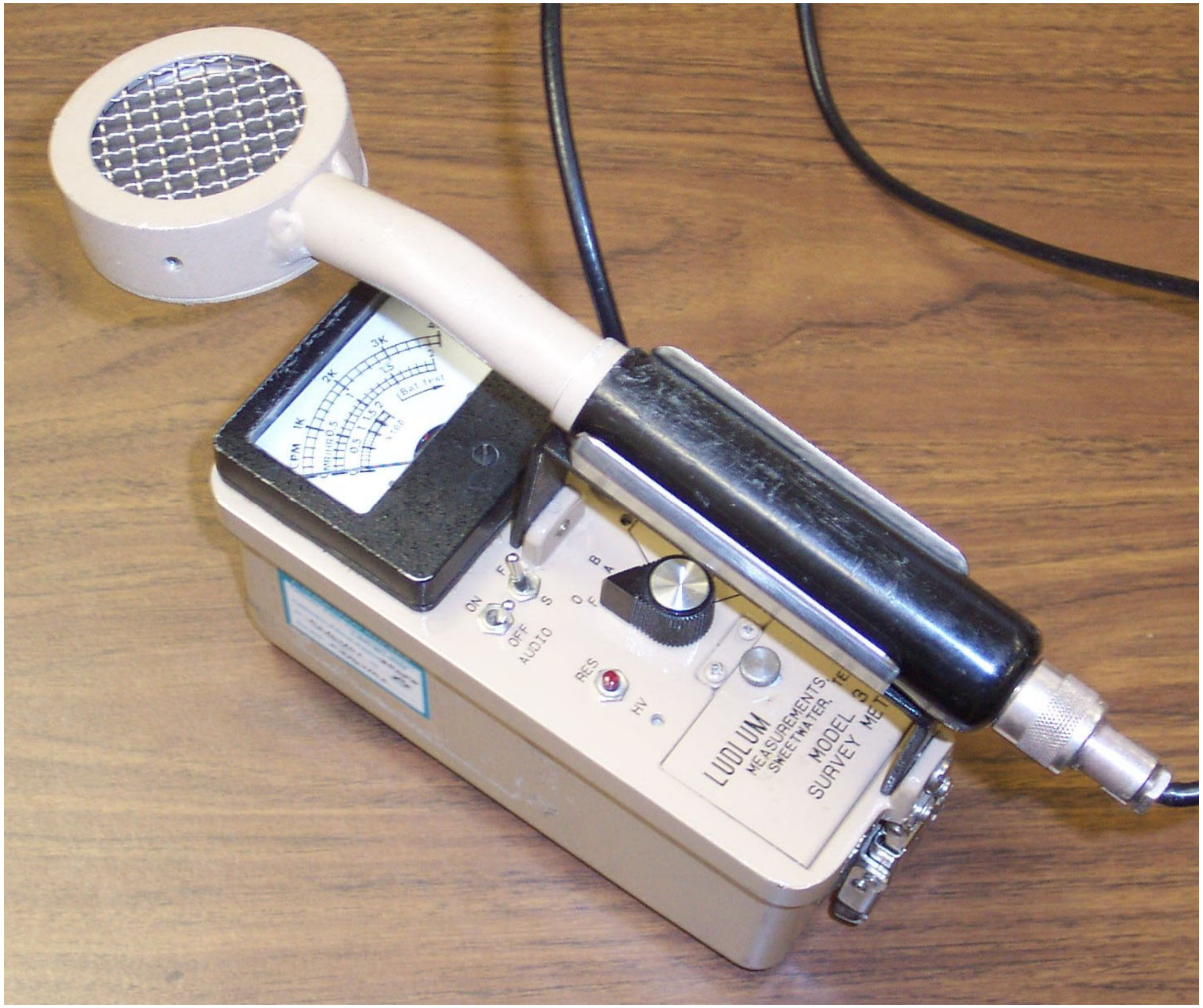


Electron-Ion Pairs
CUT AWAY VIEW
Thin Window
Insulator
Ionizing Radiation
Anode Wire
Gas Container and Cathode



Cathode
Input Window
Anode
Gamma Radiation
Counter
Resistor
0042
R
Voltage Source

Typical GM Counter



GM counters (cont.)

- GM detectors suffer from extremely long dead times – seldom used when accurate measurements are required of count rates greater than a few hundred counts per second
- Portable GM survey meter may become paralyzed in a very high radiation field – should always use ionization chamber instruments for measuring such fields

Scintillation detectors

- Scintillators are used in conventional film-screen radiography, many digital radiographic receptors, fluoroscopy, scintillation cameras, most CT scanners, and PET scanners
- Scintillation detectors consist of a scintillator and a device, such as a PMT, that converts the light into an electrical signal