ESSENTIAL INSTRUMENTATION

SOURCES AND DETECTORS OF RADIATION

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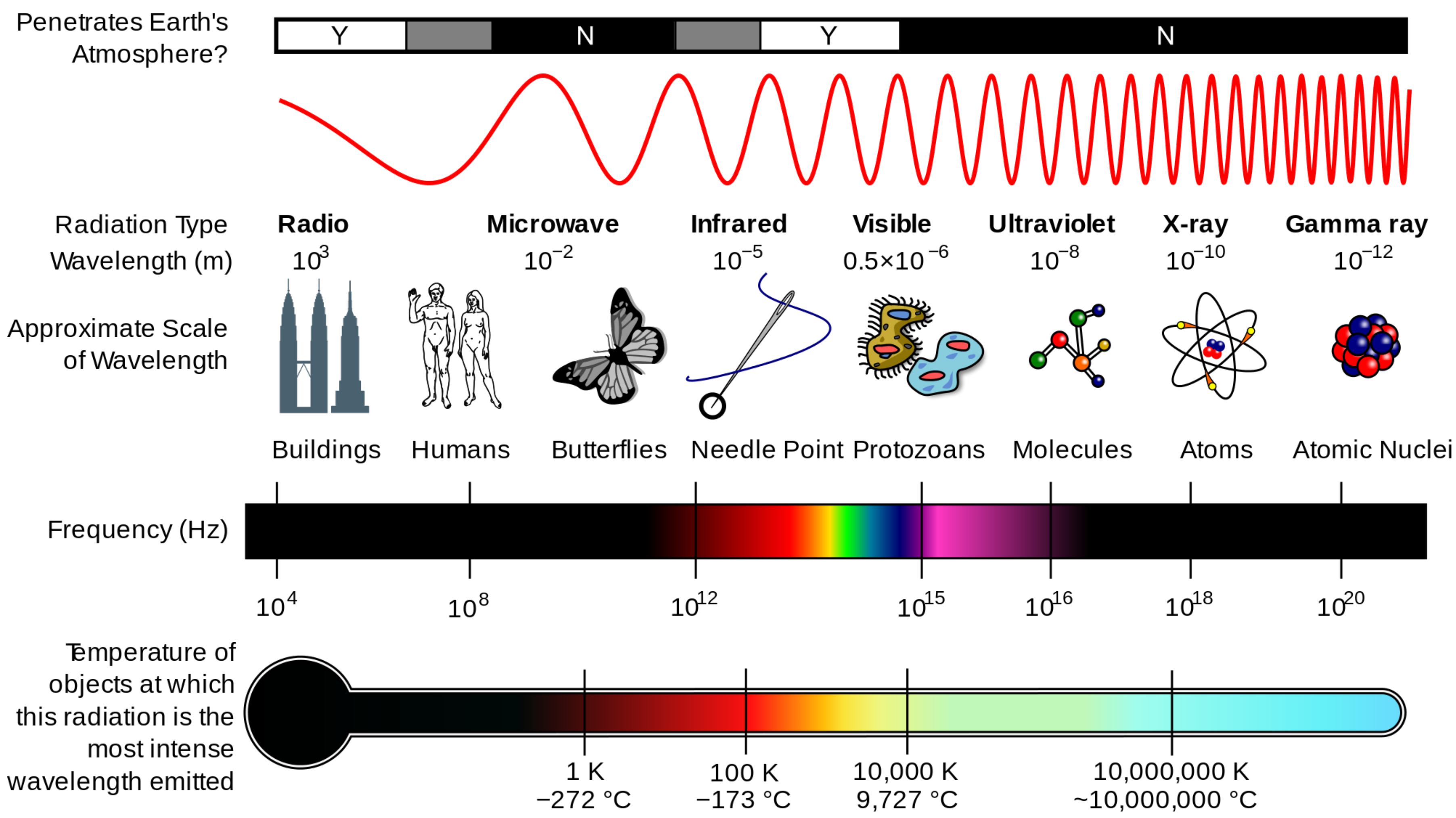

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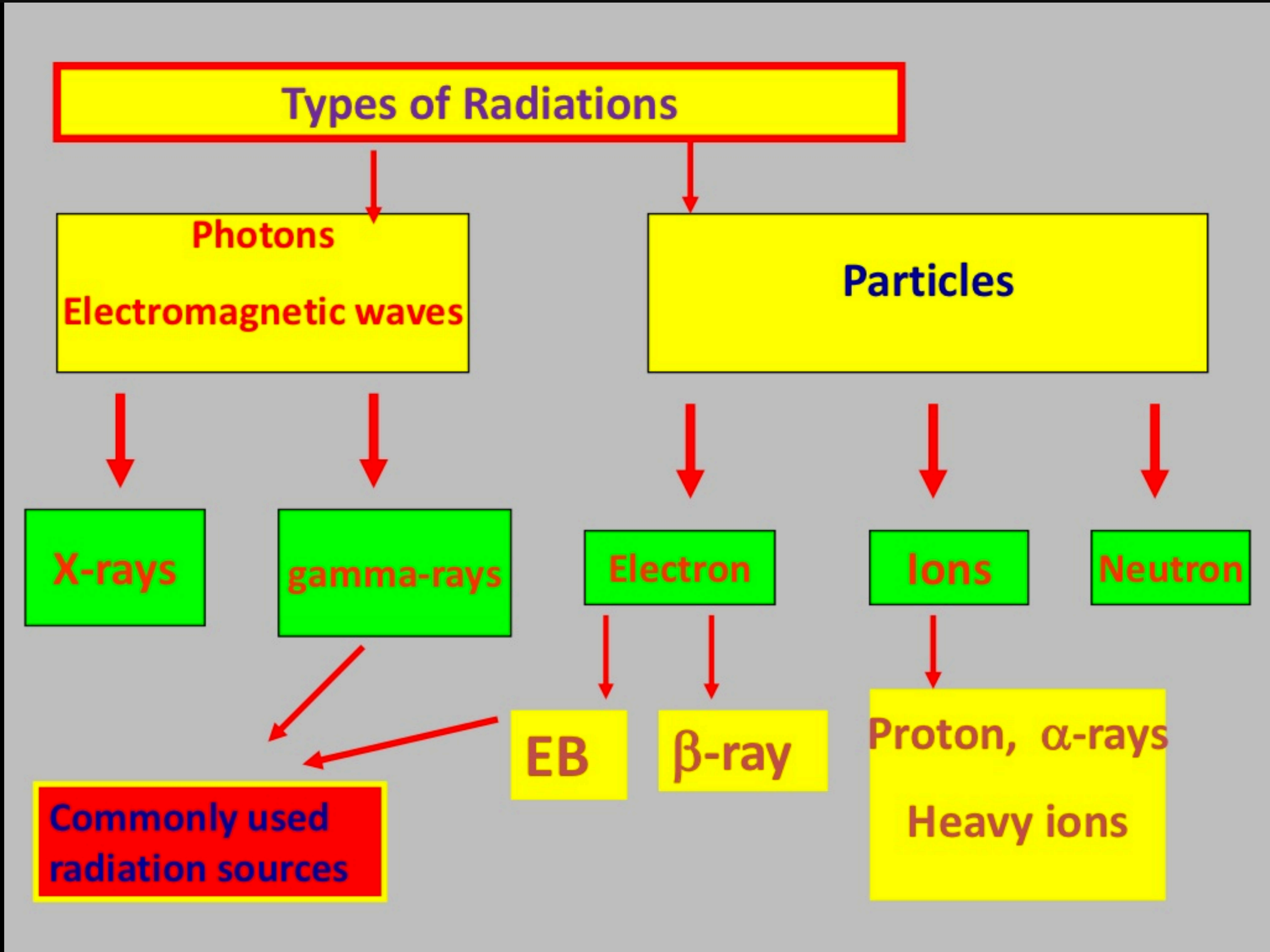

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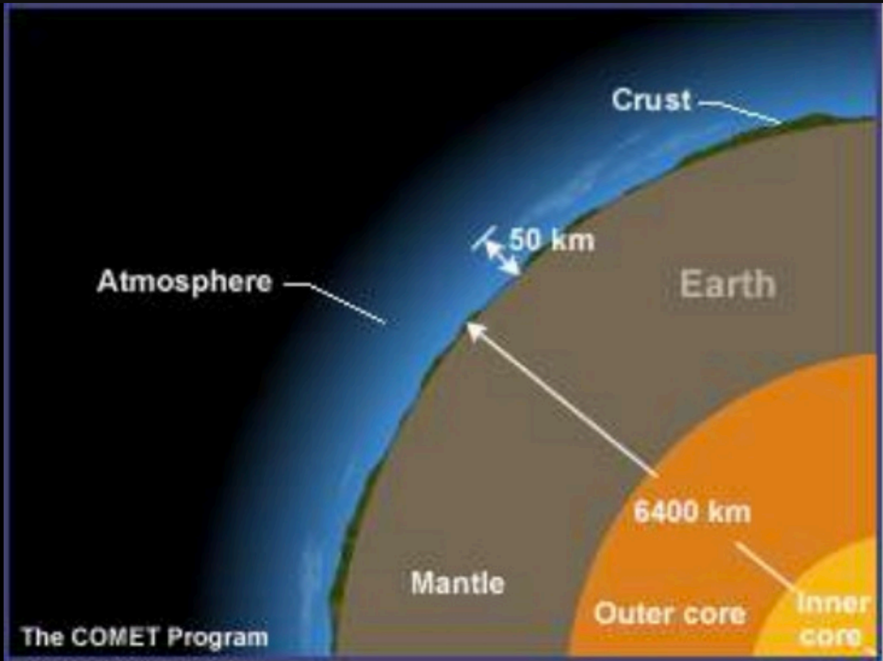
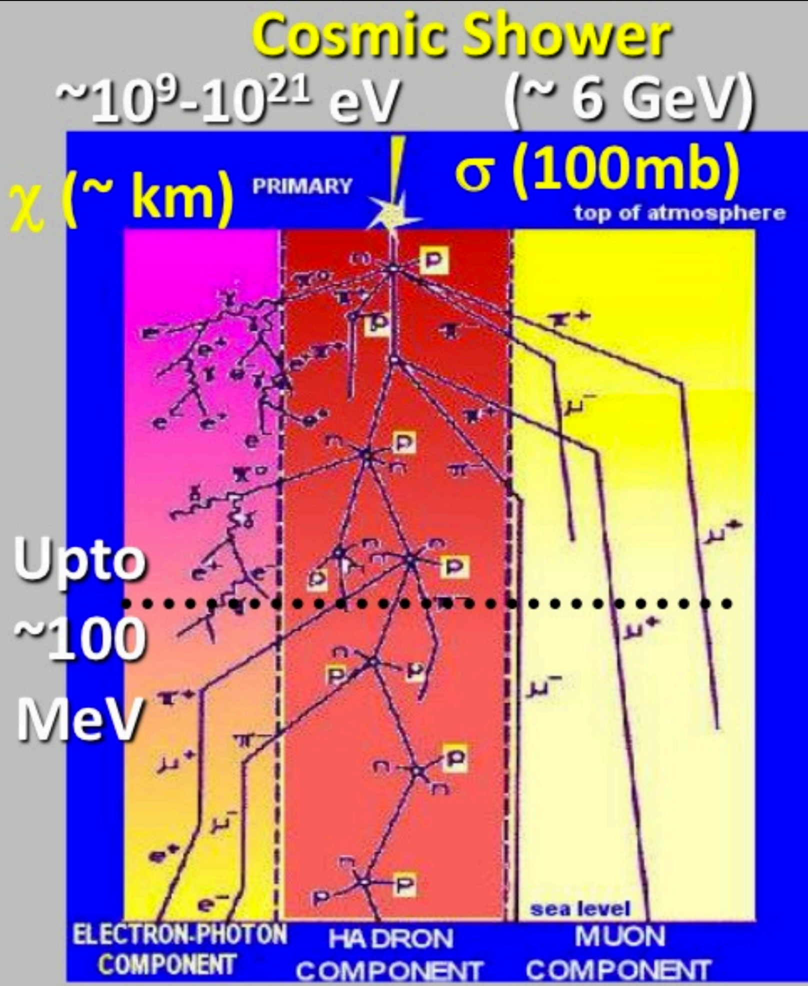


- Interact with atmospheric nuclei & produce secondary particles (muons, electrons, photons, neutrons: responsible for cosmic dose)



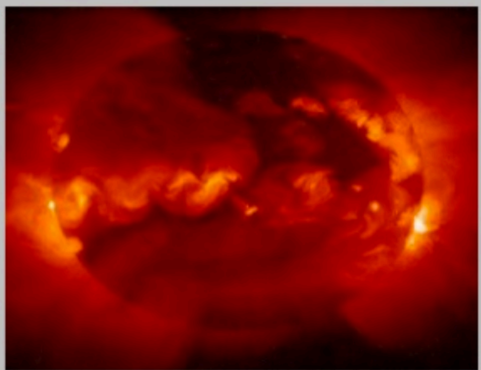
	Flux	%
H	1300	92.9
He	88	6.3
>He	10.7	1.06

The Neutron Sources

Cosmic radiations & High-energy particle accelerators are well-known neutron sources

Cosmic rays: 2 types

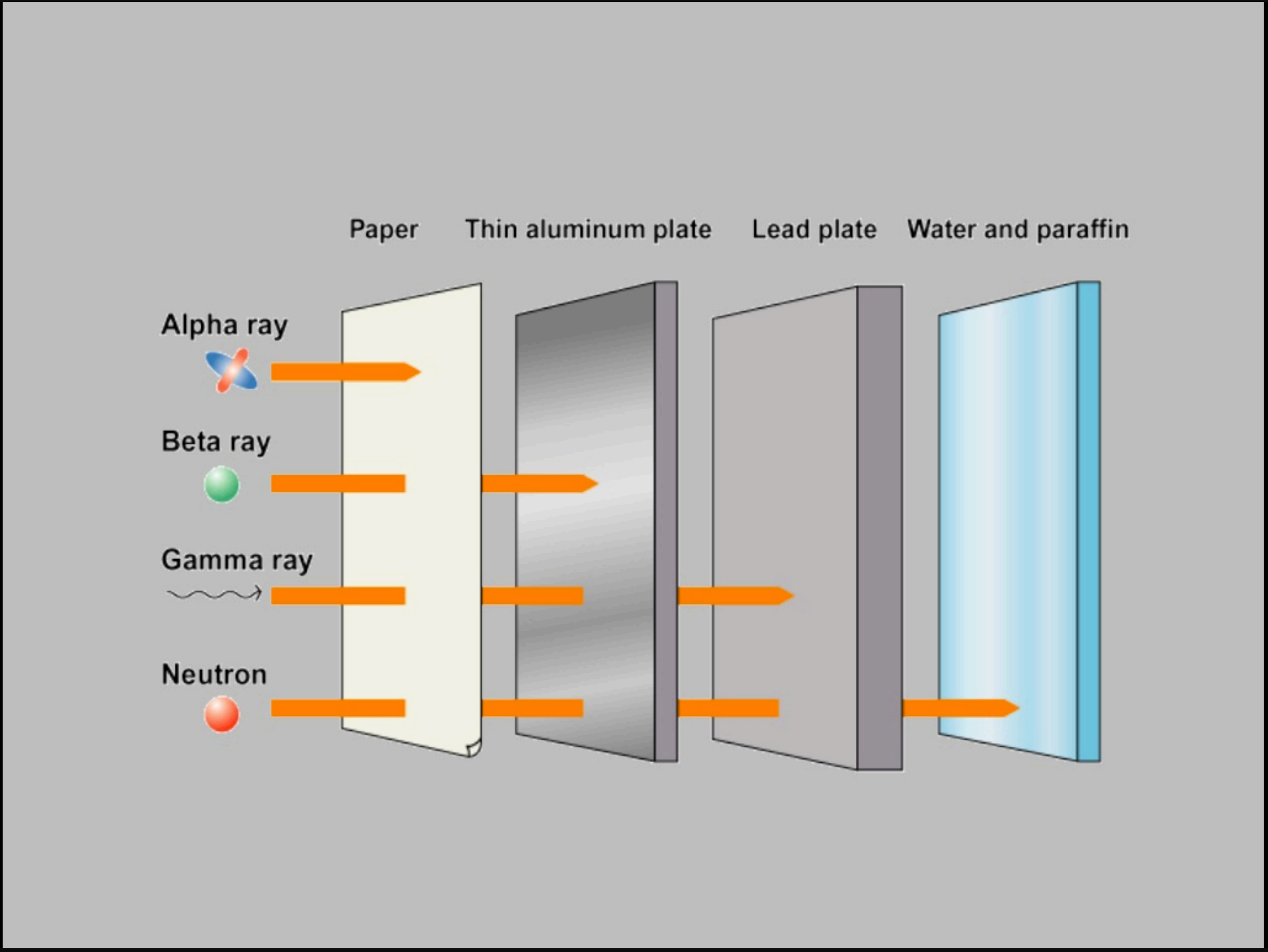
Galactic



Solar

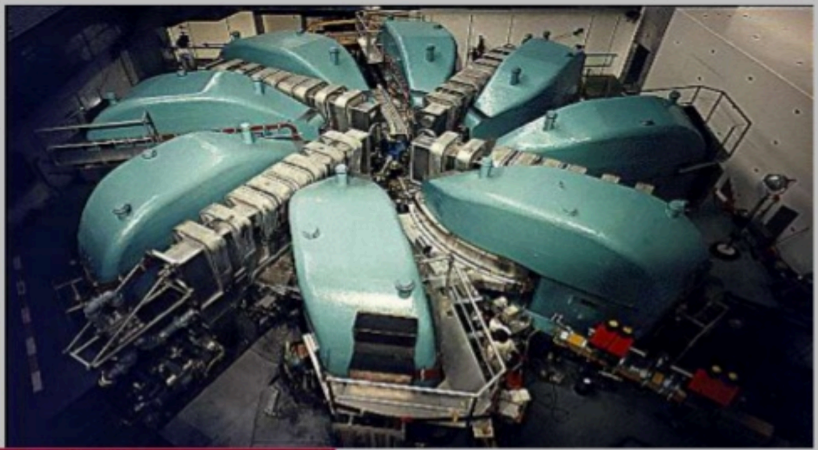
High-Energy Particle accelerators

SOURCES AND DETECTORS OF RADIATION



SOURCES AND DETECTORS OF RADIATION

CYCLOTRONS / SYNCHROTRONS /LINEAR ACCELERATORS

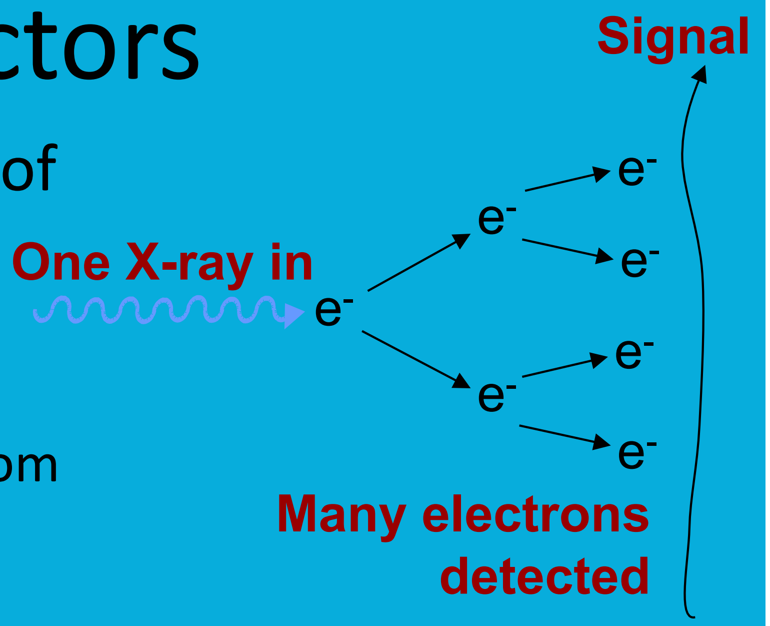


Overview

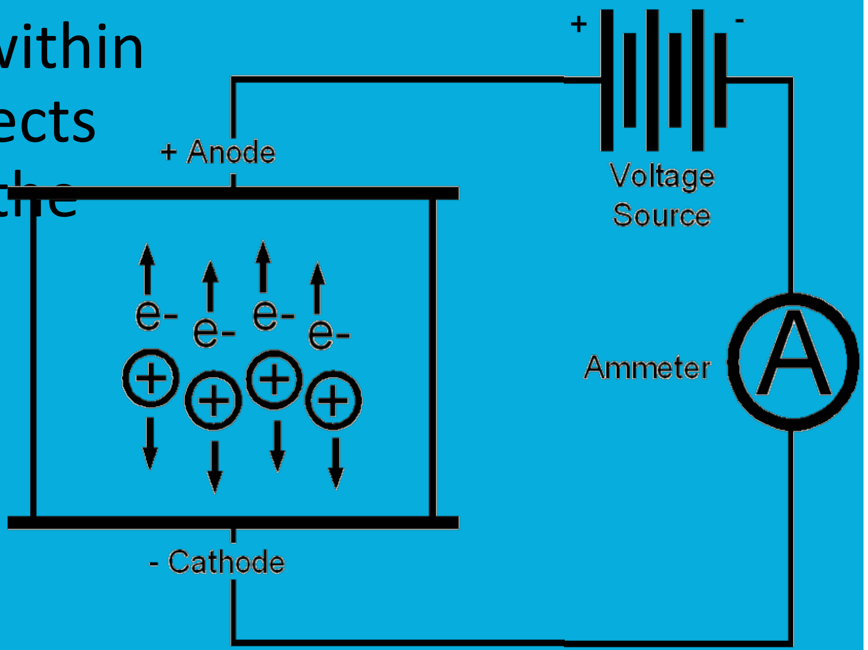
- Four methods for detecting ionizing radiation:
  1. Ions collected to produce signal
  2. Amplification of ionization to produce stronger signal
  3. Fluorescence of a substance that has absorbed energy from radiation
  4. Radiation-induced chemical reactions
- Three major types of detection instruments:
  1. Nuclear instrumentation
  2. Portable survey instruments and area monitors
  3. Personnel monitoring devices

Gas-Filled Detectors

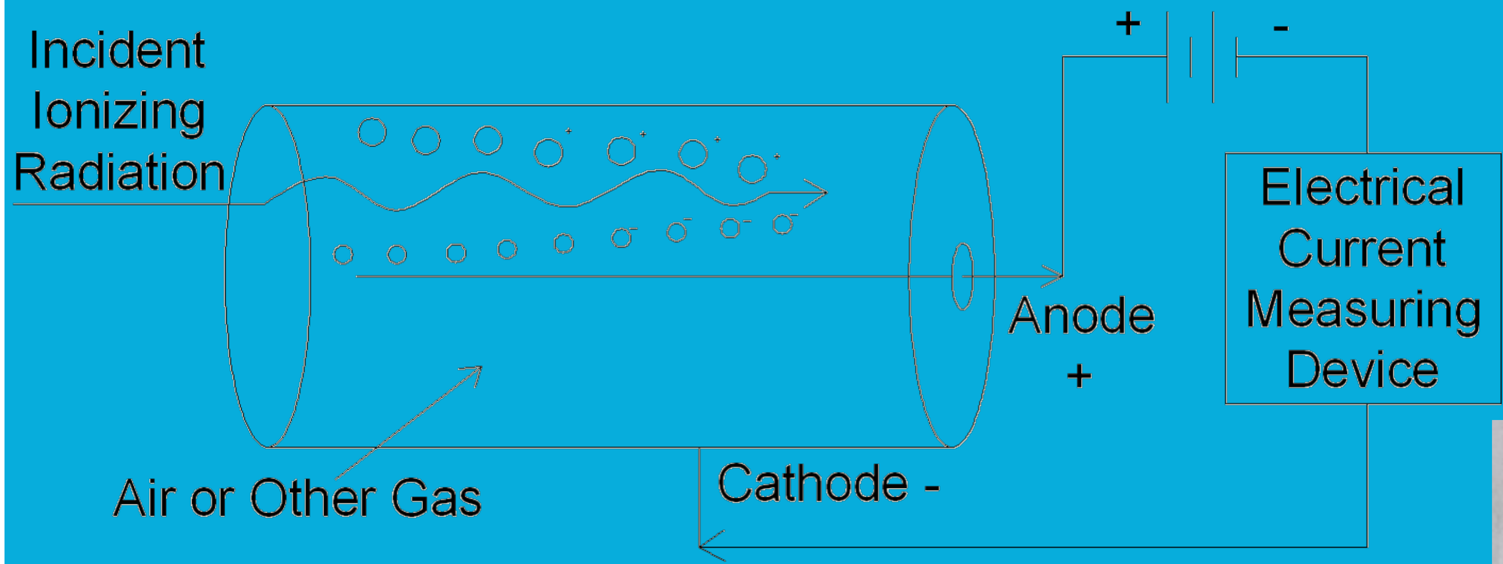
- Detect incident radiation by measurement of two ionization processes
  - Primary process: ions produced directly by radiation effects
  - Secondary process: additional ions produced from or by effects of primary ions
    - Townsend Avalanche



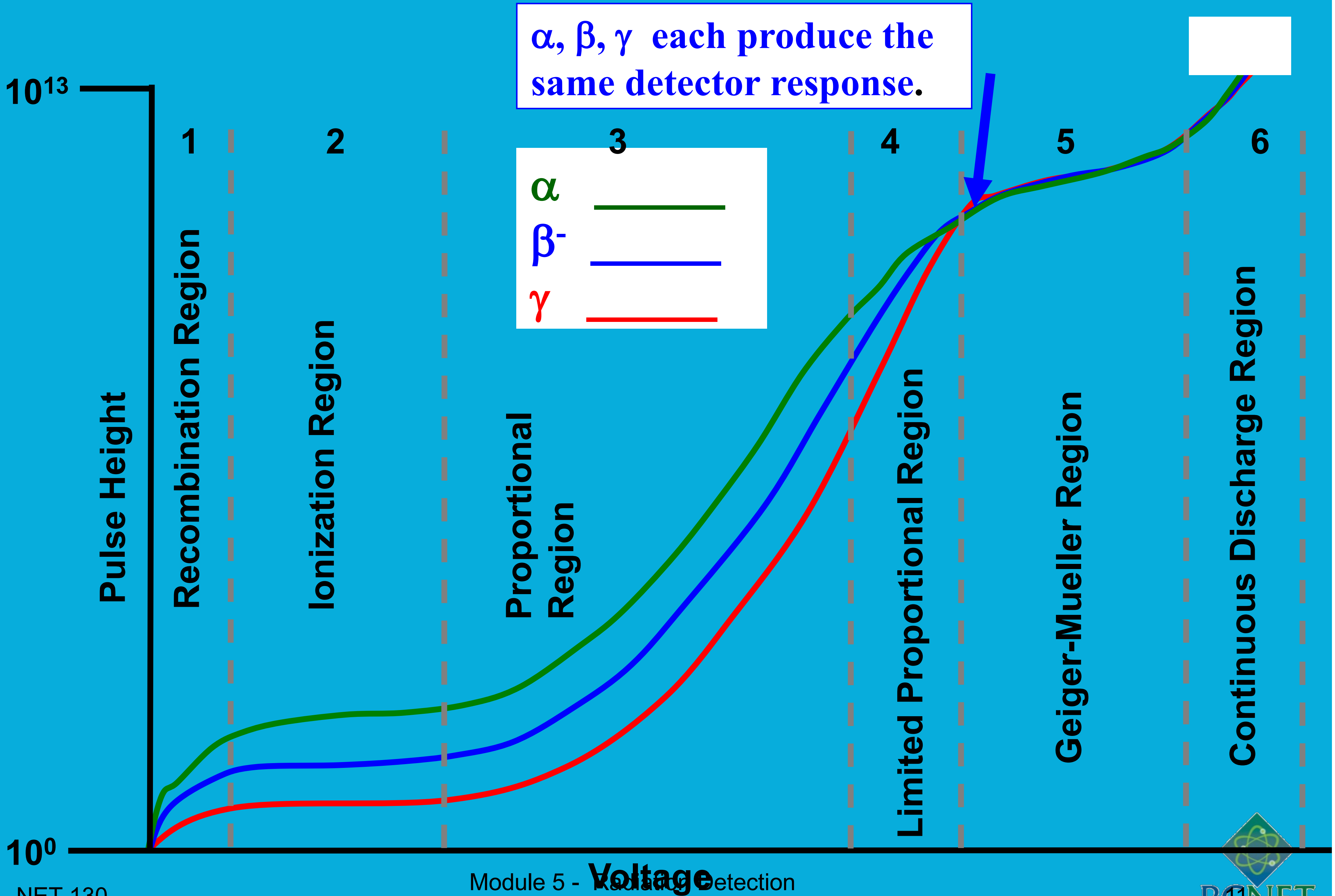
- Primary and secondary ions produced within the gas are separated by Coulombic effects and collected by charged electrodes in the detector
  - Anode (positively charged electrode)
    - Collects the negative ions
  - Cathode (negatively charged electrode)
    - Collects the positive ions



Gas-Filled Detectors



Six-Region Gas Amplification Curve



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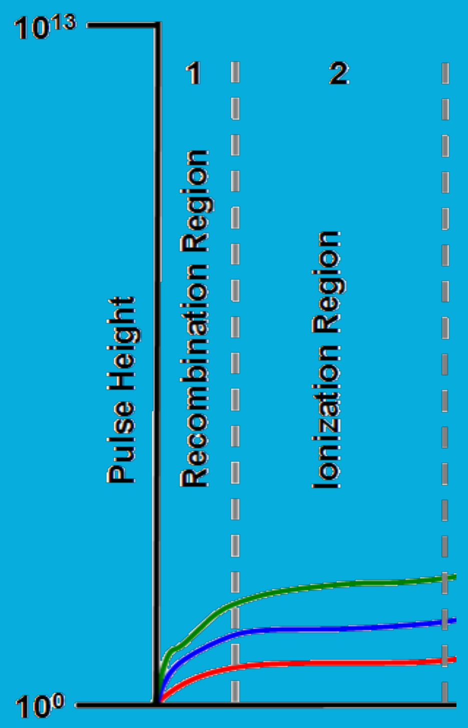


1. Recombination Region
   - Applied voltage too low
   - Recombination occurs
   - Low electric field strength

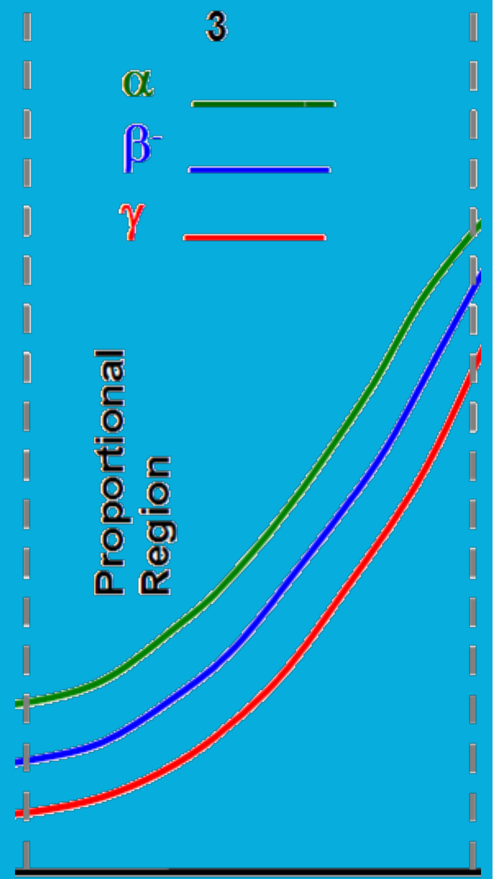
2. Ionization Chamber Region (aka Saturation Region)
   - Voltage high enough to prevent recombination
     - All primary ion pairs collected on electrodes
   - Voltage low enough to prevent secondary ionizations
   - Voltage in this range called saturation voltage
   - As voltage increases while incident radiation level remains constant, output current remains constant (saturation current)

Six-Region Gas Amplification Curve

3. Proportional Region

- Gas amplification (or multiplication) occurs
  - Increased voltage increases primary ion energy levels
  - Secondary ionizations occur
  - Add to total collected charge on electrodes
- Increased output current is related to # of primary ionizations via the proportionality constant

  (aka gas multiplication factor)
  - Function of detector geometry, fill-gas properties, and radiation properties



Six-Region Gas Amplification Curve

4. Limited Proportional Region
- Collected charge becomes independent of # of primary ionizations
- Secondary ionization progresses to photoionization (photoelectric effect)
- Proportionality constant no longer accurate
- Not very useful range for radiation detection

Six-Region Gas Amplification Curve

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
   - Dead time limits the number of radiation events that can be detected
     - Usually 100 to 500 μs

Six-Region Gas Amplification Curve

6. Continuous Discharge Region
   - Electric field strength so intense that no initial radiation event is required to completely ionize the gas
   - Electric field itself propagates secondary ionization
   - Complete avalanching occurs
   - No practical detection of radiation is possible.

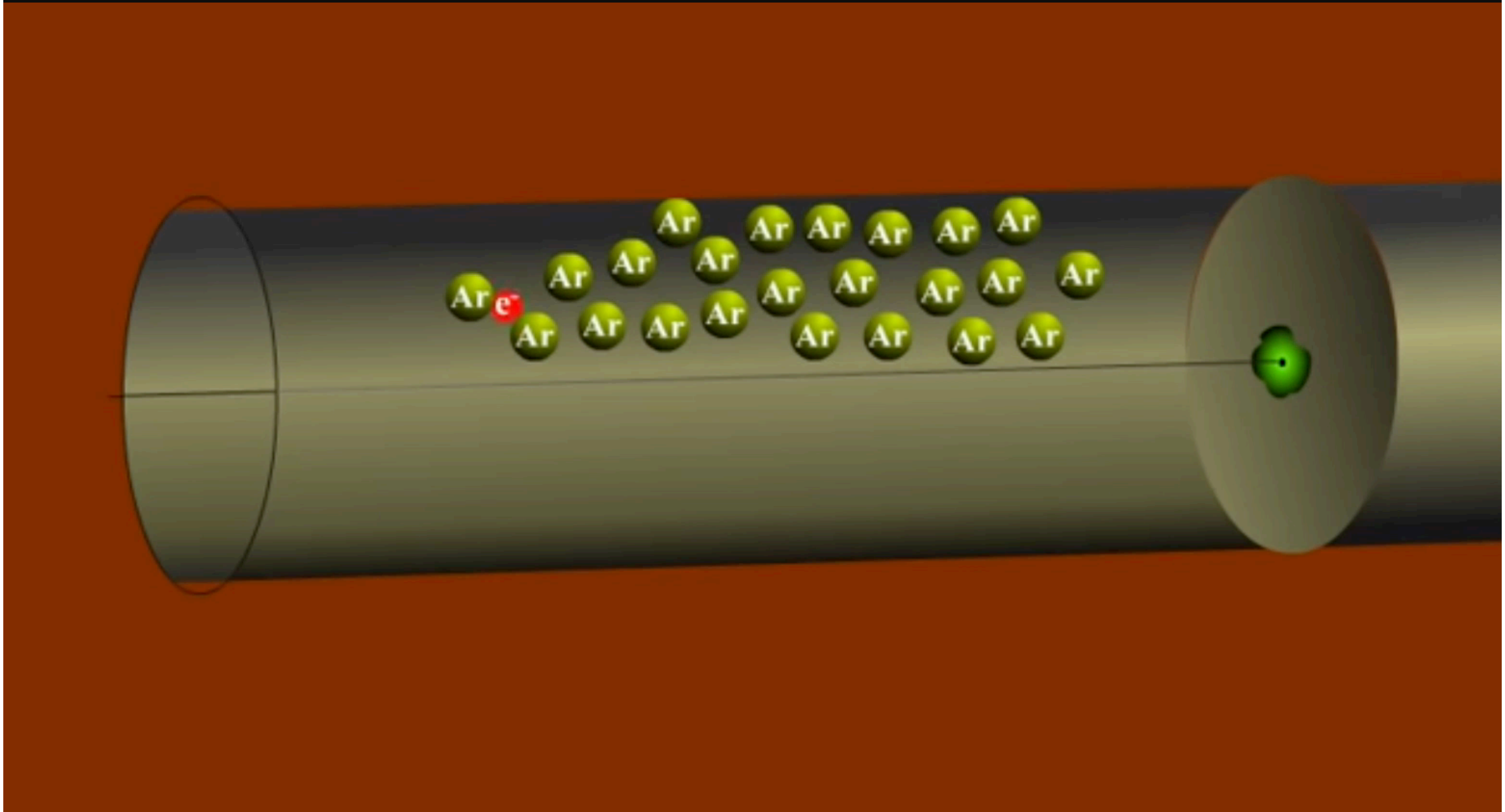
Proportional Gas-Filled Detectors

- Can discriminate between α, β, and γ radiation
  - **Pulse height discrimination**: electronically filter out pulses below or above expected height for radiation type of interest
- Less sensitive over long range than GM
- Include:
  - Portable neutron radiation survey meters
  - Personnel contamination monitoring

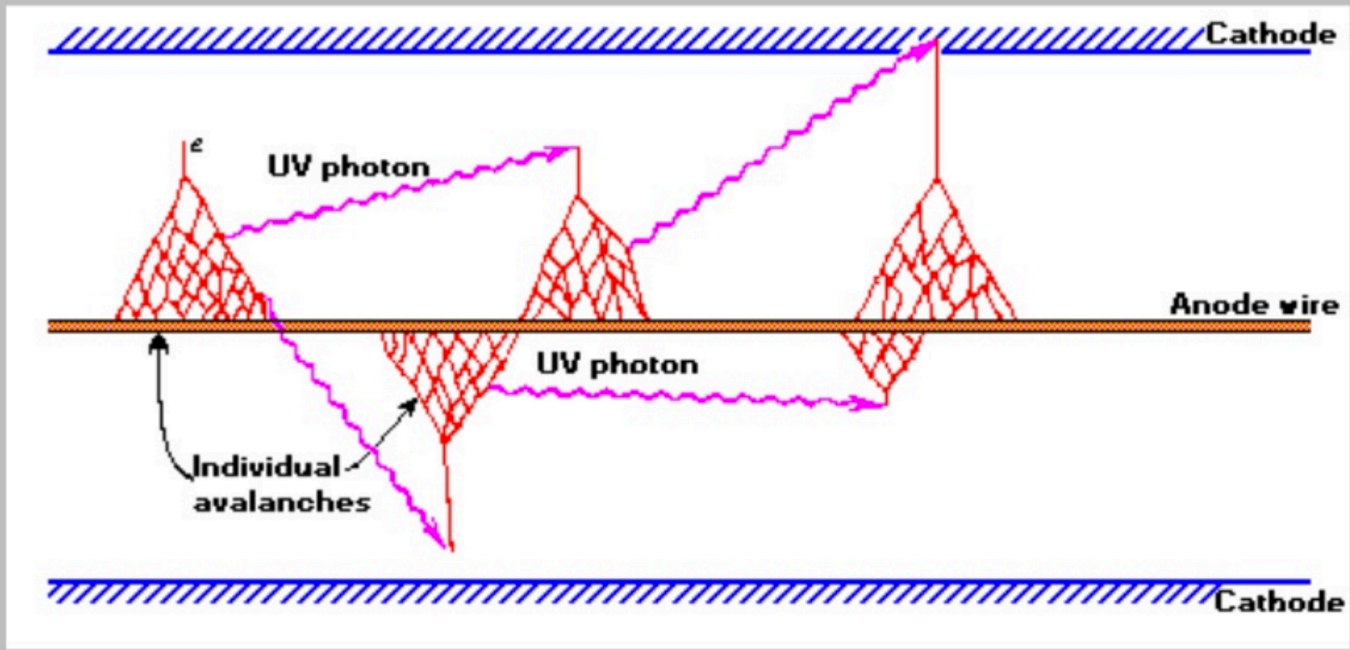
Geiger-Mueller Gas-Filled Detectors

- Include:
  - Area radiation monitors
  - Portable high-range radiation survey meters (Teletector)

SOURCES AND DETECTORS OF RADIATION



GEIGER MULLER TUBE



Geiger-Mueller 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)

Geiger-Mueller Gas-Filled Detectors

- Some GM detectors detect γ only
  - Solid casing
- Some detect α, β, and γ
  - α, β radiation: short travel range
    - Cannot penetrate detector casing
  - Mylar window to allow α and β radiation to enter
  - α and β can be separately detected by using different window types and thicknesses to filter incident radiation
  - Shield must be placed over window to detect γ
    - Blocks α and β

SOURCES AND DETECTORS OF RADIATION

GAS FILLED DETECTORS

Gamma Ion Chamber
Criticality Alarm Systems

Gamma Ion Chamber
Area Monitoring

$B^{10}F_3$ filled counter.

Neutron Monitoring

He^3 filled counter.

Fission Detector with MI cable for Source Range Monitoring (BWR)

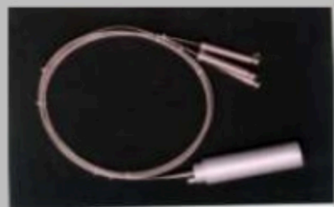
Fission Detector with MI cable for Intermediate Range Monitoring(BWR)

Neutron Monitoring

Gamma Compensated neutron Ion chamber

Self Powered Neutron Detector

Uncompensated Neutron Ion Chamber with MI cable for Power Range Monitoring in PHWRs



Scintillation Detectors

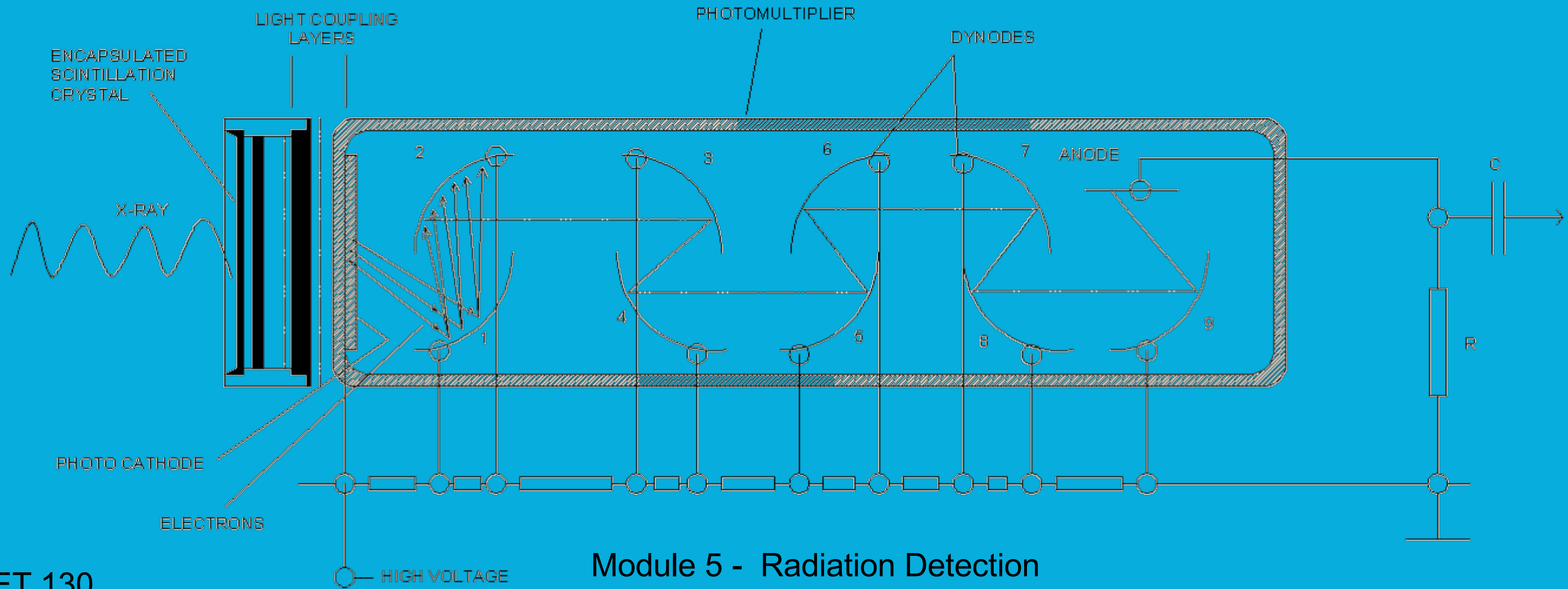
- Detect radiation by induction of **luminescence**
  - Absorption of energy by a substance with the subsequent emission of visible radiation (photons)

- Incident radiation interacts with the scintillator material
- Excites electrons in material
- Electromagnetic radiation emitted in the visible light range

- Common scintillator materials
  - Anthracene crystals
  - Sodium iodide crystals
  - Lithium iodide crystals
  - Zinc sulfide powder
  - Lithium iodide, boron, and cadmium can be used to detect neutrons

6 Steps of Scintillation Detection

- Inside scintillator:
  1. Excitation due to absorption of radiation
  2. Emission of light photons from de-excitation
  3. Transit of light to photocathode inside photomultiplier tube
- Inside photomultiplier tube:
  4. Production of photoelectrons in photocathode
  5. Multiplication of photoelectrons
- Outside scintillator and photomultiplier tube:
  6. Conversion of electronic detector output to useful information



SOURCES AND DETECTORS OF RADIATION

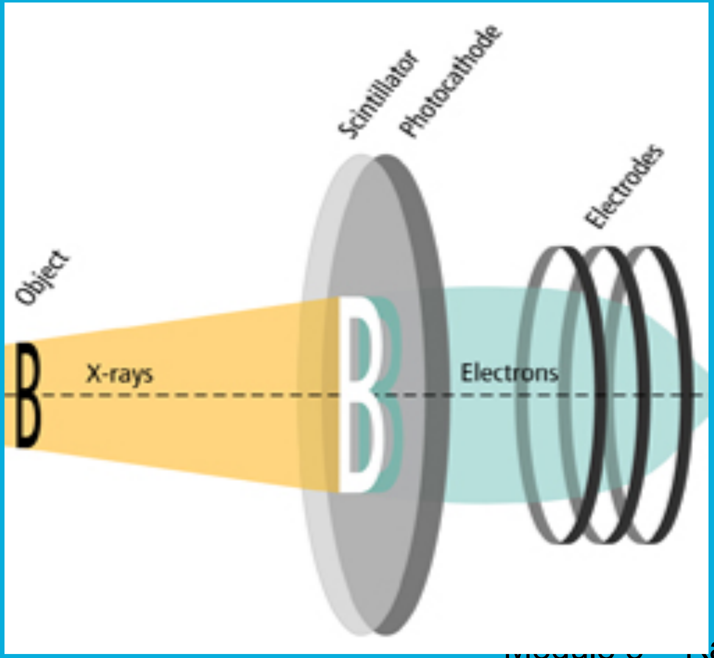
Common Scintillator Materials

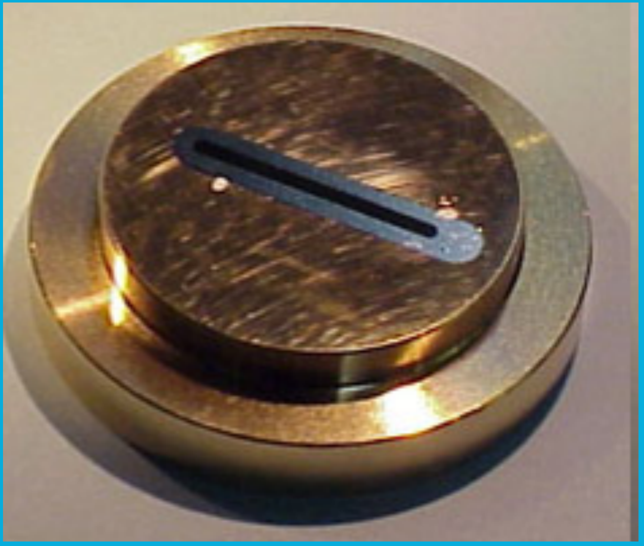
- Anthracene crystals
- Sodium iodide crystals
- Lithium iodide crystals
- Zinc sulfide powder

- Lithium iodide, boron, and cadmium can be used to detect neutrons

Photocathode

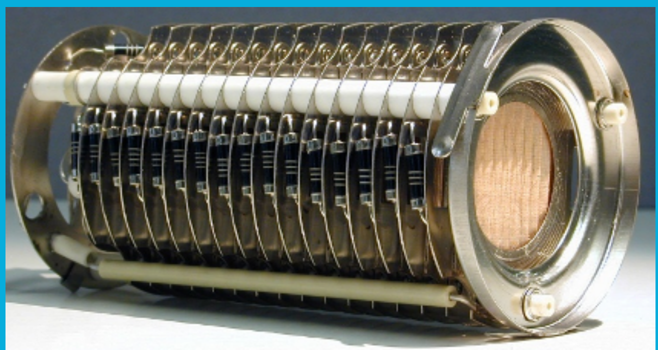
- Light-sensitive material that absorbs photons and emits photoelectrons
- Common material: Antimony-Cesium
- Emits about one electron for every 10 photons absorbed

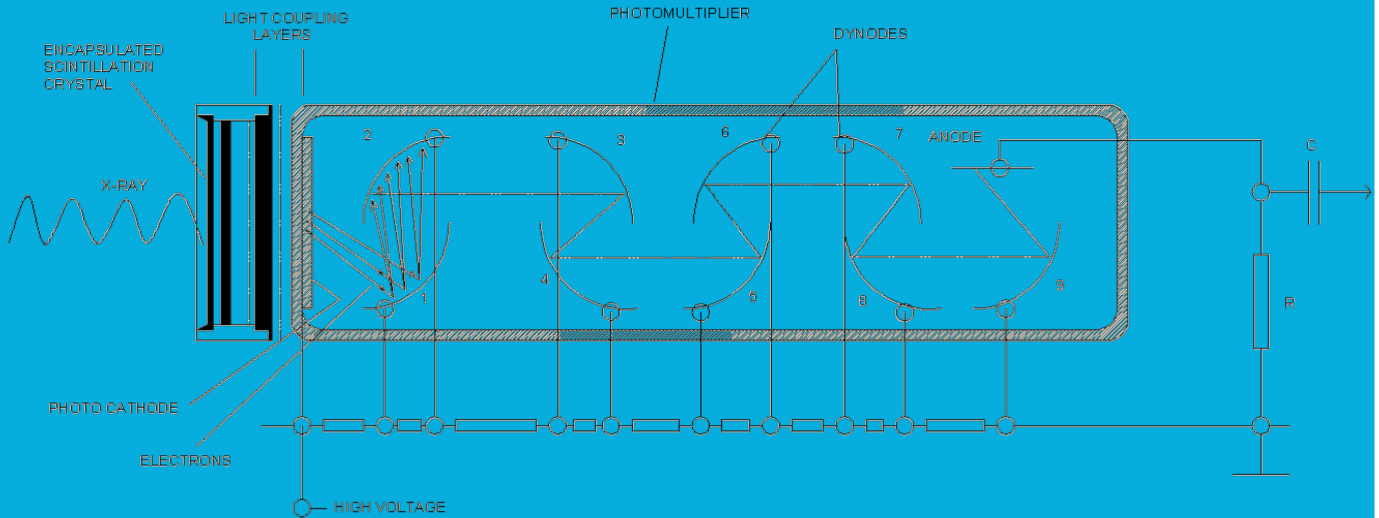




Photomultiplier Tube: Dynodes

- Photoelectrons strike successive dynodes and are multiplied (secondary electron production)
- Amplifies the output signal
- If tube has 10 dynodes, total gain would be around 10^6
- Typical tubes made with 6 to 14 dynodes



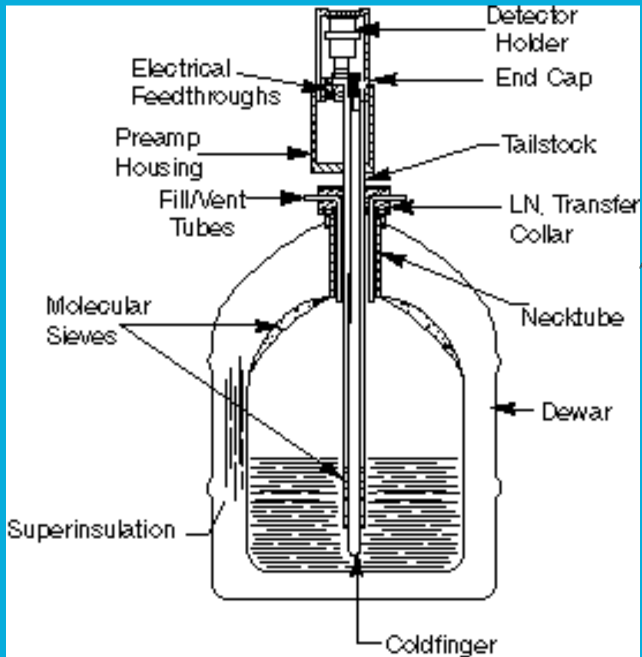


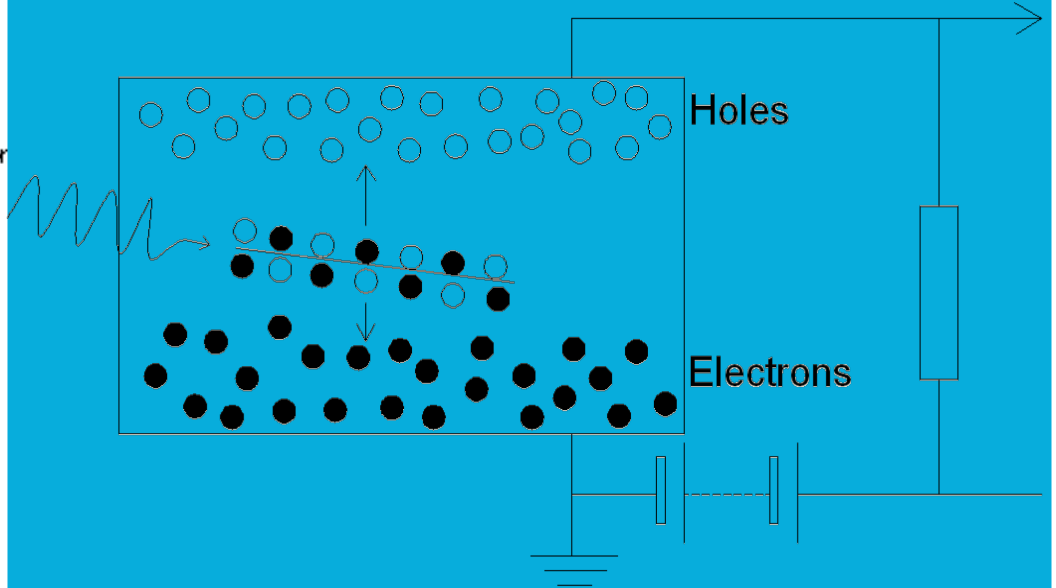
Semiconductor Detectors

- Operation similar to gas-filled detectors, but chamber filled with solid semiconductor material
- Crystalline material whose electrical conductivity is intermediate between that of a good conductor and a good insulator
- Benefits compared to other types
  - Very little fluctuation in output for a given energy of radiation
  - Fast

Semiconductor Detectors

- Energy transfer from radiation to semiconductor target produces a freed electron and an electron vacancy, or **hole**
- Electrons travel to the anode
- Hole "travels" toward the negative electrode
  - Not physically
  - Successive exchanges of electrons between neighboring molecules in the crystalline lattice





Semiconductor Detectors: Pros/Cons

- Pros
  - Fast response time
    - Due to high mobility of electrons and holes
    - Takes longer for ions to physically travel through space in a gas-filled detector
  - Less statistical fluctuations for any given radiation energy
    - A smaller amount of energy required to produce electron-hole pair in a semiconductor than an ion pair in a gas
    - For a given energy, 8 to 10 times as many charge-carrying pairs are produced in semiconductors as in gases
  - Total charge collected varies linearly with radiation energy
- Cons
  - Very sensitive to heat: must be cooled to eliminate error
  - Photomultiplier output very weak
    - Powerful amplifiers needed in the external circuit

Detection Systems

- Two main components:
  1. Detector
     - Gas-filled, scintillation, or semiconductor
  2. Measuring apparatus
     - Converts signal output from detector to usable information for the operator
- Detection system categories, by output type:
  – Pulse-type output
  – Mean-level output
- Detection system categories, by application:
  – Nuclear instrumentation
  – Portable survey instruments and area monitors
  – Personal dosimetry

Detection Systems: Output Type

- 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
  - "Frisker"-type survey instruments found near any contaminated area access point

- Mean-Level Output:
  - radiation events occurring at a high rate prevent resolution into individual pulses
  - thus events are averaged over time, and recorded as a "rate", "level" or "total" over time
  - Reactor power level instrumentation uses this type of detection system, due to high neutron flux

Nuclear Instrumentation (NI)

- NI detectors are used to measure/record neutron flux (η) as a measure of reactor power level
- Range of η flux is wide, spanning from:
  1. Shutdown
  2. Reactor start-up
  3. 100% power
- To accurately monitor η population at all power levels, there are three overlapping detector ranges
  – Source range: (10^0 – 10^6)
  – Intermediate range: (10^1 – 10^{10})
  – Power range: (10^{10} – 10^{12})

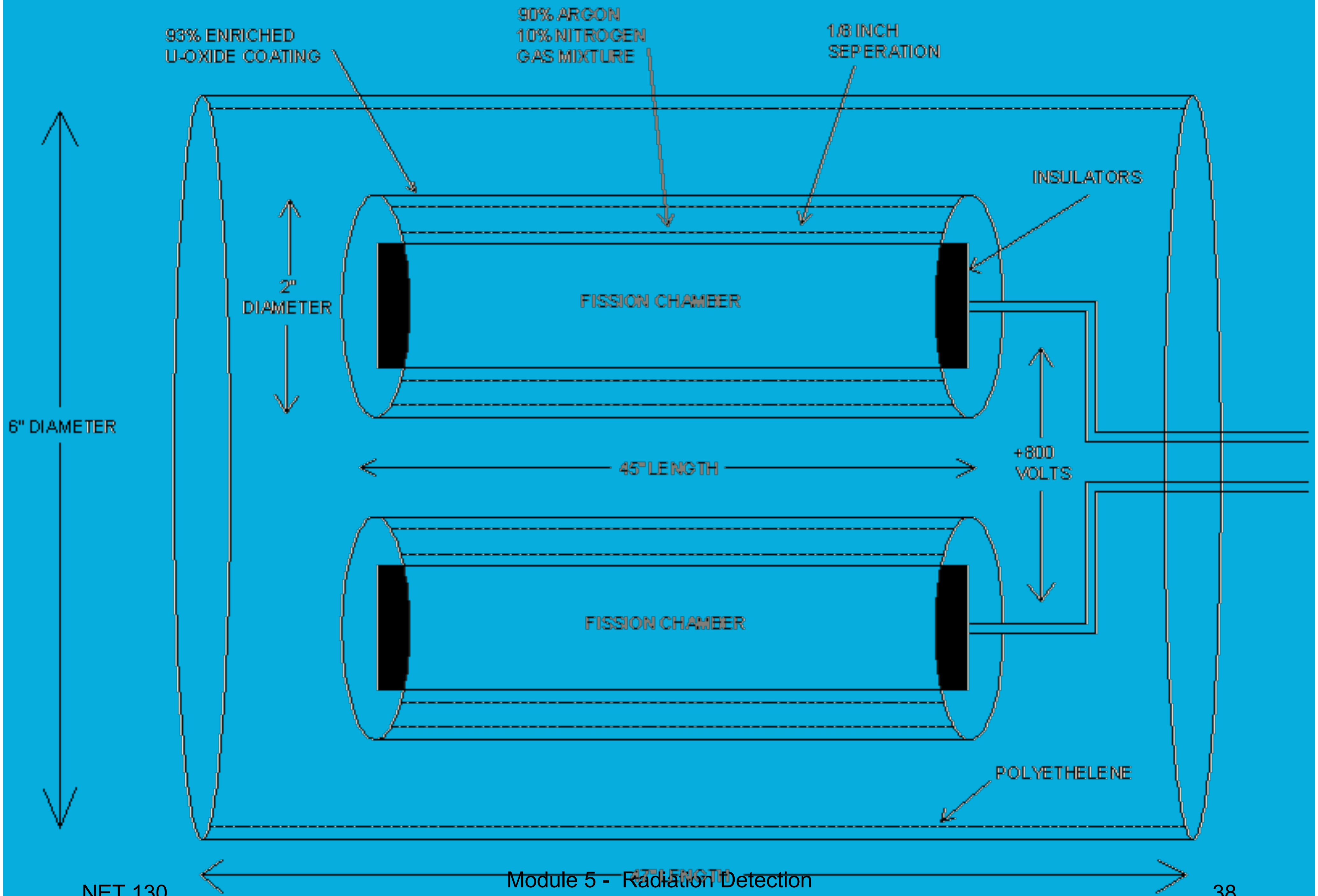
Neutron Energy Ranges

- **Fast neutrons** have an energy > 1 eV
- **Slow neutrons** have an energy less than or equal 0.4 eV.
- **Hot neutrons** have an energy of about 0.2 eV.
- **Thermal neutrons** have an energy of about 0.025 eV.
- **Cold neutrons** have an energy from 5x10−5 eV to 0.025 eV.

NI: Fission-Chamber Detectors

- Neutron detection in **source and intermediate ranges**
- Gas-filled ionization-type detector
- Inner “cans” coated with U-235 lining
- Fast neutrons exiting the core are thermalized by the time they make their way inside the F-C detector
  - Interact with materials outside the core
  - Interact with the plastic covering of the detector
- Thermal neutrons lead to fission of the U-235 lining inside the detector
- Reactor core neutron flux is then measured as a product of the fission of U-235 in the F-C detector

SOURCE RANGE FISSION CHAMBER DETECTOR



Fission-Chamber Output Signal

- Pulse height discrimination implemented in order to pass only the signal portion due to neutron effects
- Pulse discriminator bias: the selective value for pulses
- Products of incident thermal neutrons: fission fragments with average energy of 165 MeV
- Energy of alphas from uranium isotope decay: 4 MeV
- Fission gammas: no more than 7 MeV
- The fission fragment energy due to neutron entering the detector is clearly distinct
  - Pulse is much larger than those for non-fission reactions within detector

SOURCES AND DETECTORS OF RADIATION

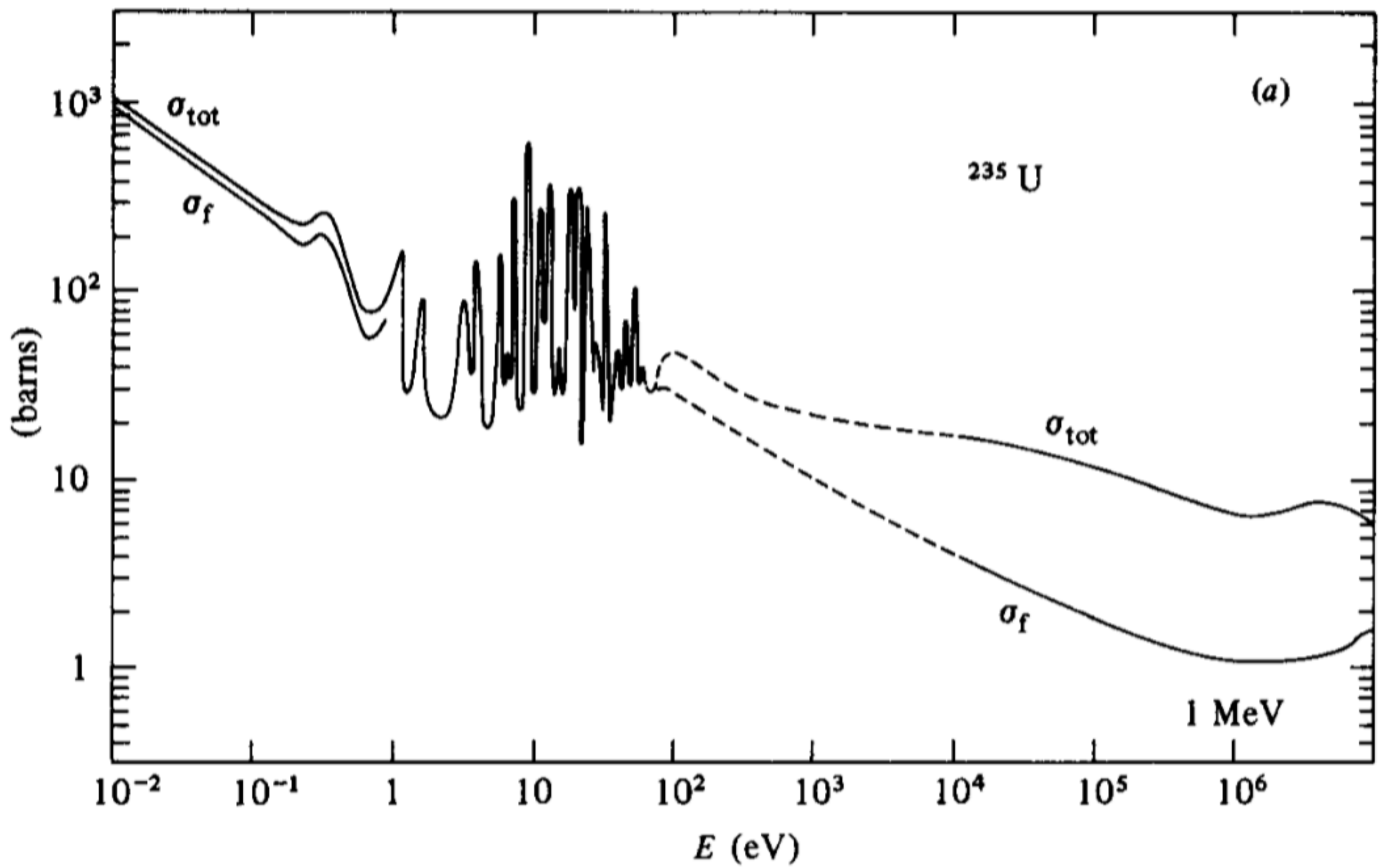


Fig. 9.1 Total cross-section σ_{tot} and fission cross-section σ_f as a function of energy for neutrons incident on (*a*) ^{235}U, (*b*) ^{238}U. In the region of the dashed lines the resonances are too close together for the experimental data to be displayed on the scale of the figures. Note that both the horizontal and vertical scales are logarithmic. (Data from Garber, D. I. & Kinsey, R. R. (1976), *Neutron Cross Sections*, vol. II, Upton, New York: Brookhaven National Laboratory.)

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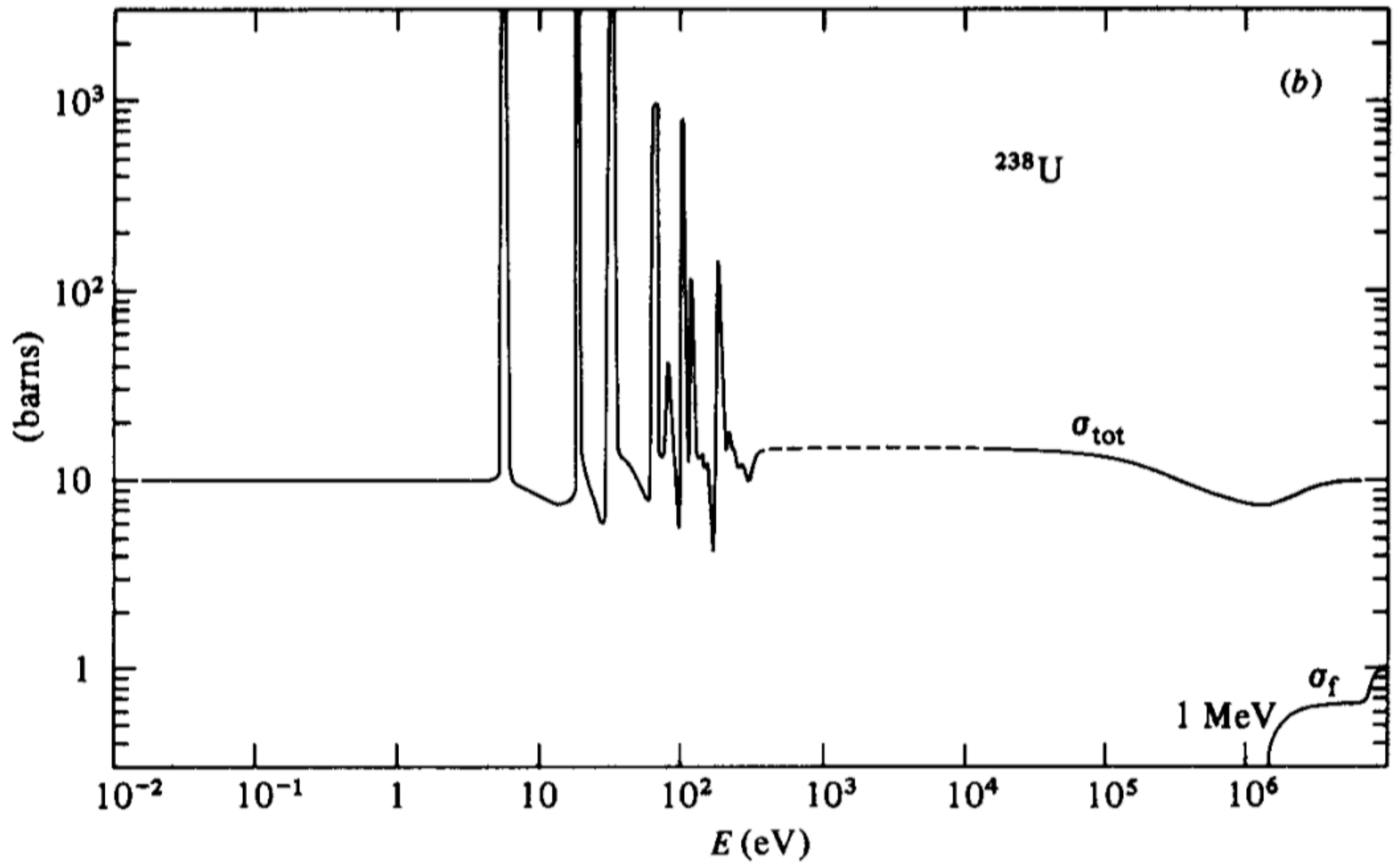

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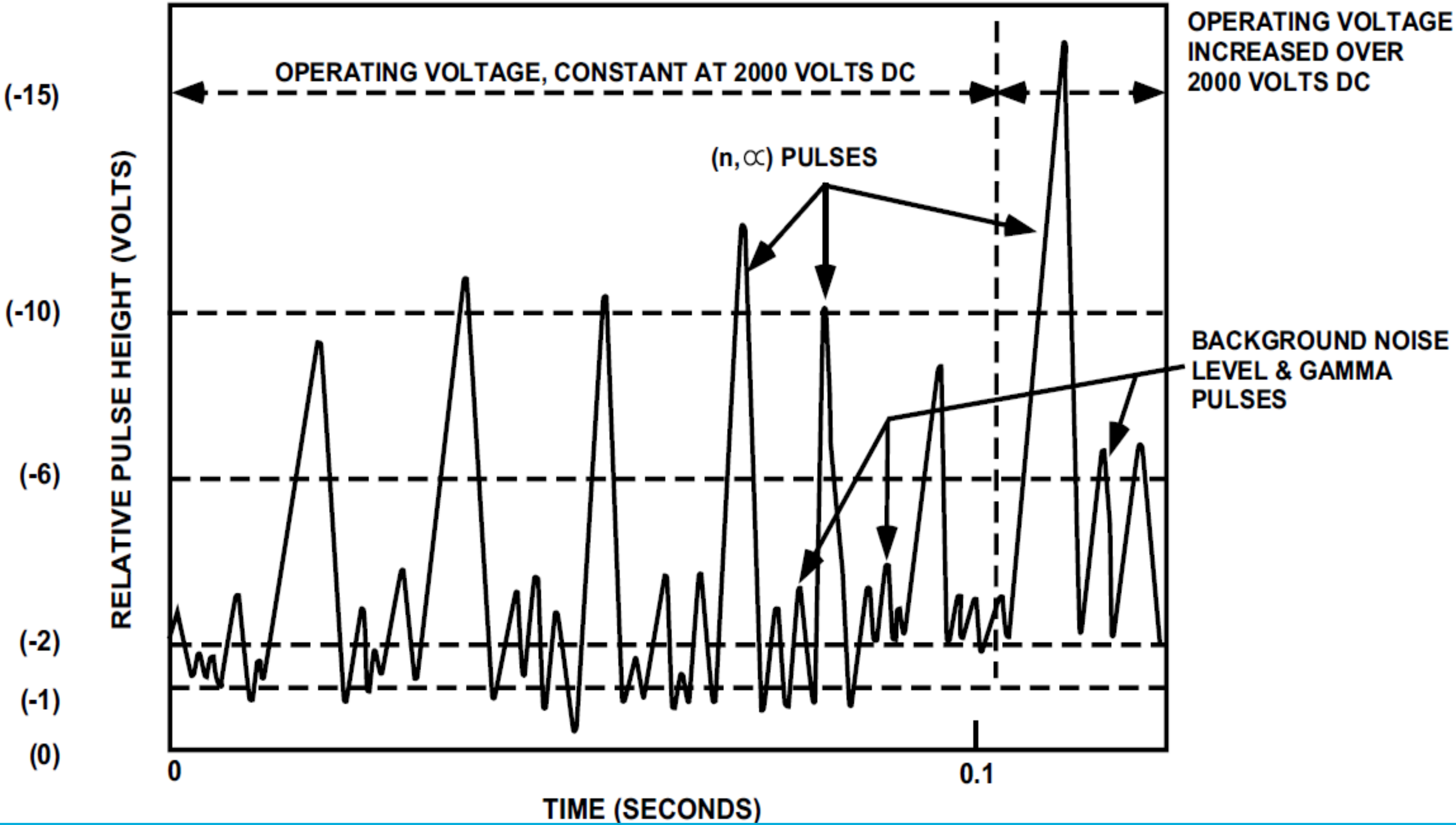
Table 9.1. *Distribution of energy release on the induced fission of a nucleus of* ^{235}U

		MeV
Kinetic energy of fission fragments		167
Kinetic energy of fission neutrons		5
Energy of prompt γ-rays		6
Sub-total of 'immediate' energy		178
Electrons from subsequent β-decays	8	
γ-rays following β-decays	7	
Sub-total of 'delayed' energy		15
Neutrino energy		12
		205

Pulse Height Discrimination



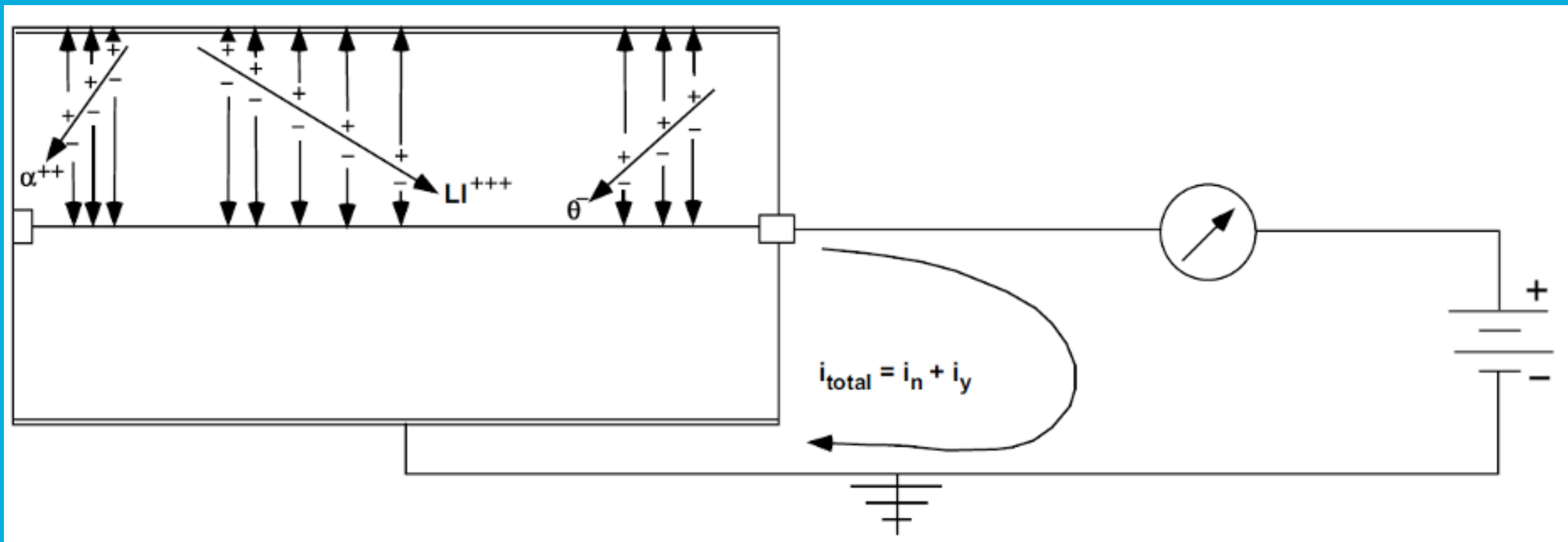
NI: Power vs. Intermediate Range

- Any power level: reactor produces both neutron and gamma fluxes
- In intermediate range, exact correlation between gamma and neutron flux is not easily predictable
- For an ion chamber to read power in the intermediate range, it must be compensated
  - Electronically cancel out gamma effects

- In **power range**, gamma flux becomes insignificant compared to neutron flux
- Gamma compensation no longer necessary

NI: Uncompensated Ion Chambers

- Monitor reactor power in the power range
  - Single boron-lined cylindrical chamber operating in the ionization chamber region
  - Mean-level output
  - Gamma-induced current typically represents only 1% of total output signal



NI: Incore Instrumentation

- Monitor power production at select locations within the core
- Verify reactor core design parameters: flux mapping
- Data only– no operational plant control
- Simpler version of fission chamber
  - Approx 0.2" diameter, 2.1" length
  - Uses uranium oxide clad in stainless steel, with helium fill gas