Lecture 7
Neutron Detection

22.106 Neutron Interactions and Applications

Spring 2010

Types of detectors

- *Gas-filled detectors* consist of a volume of gas between two electrodes
- In *scintillation detectors*, the interaction of ionizing radiation produces UV and/or visible light
- *Semiconductor detectors* are especially pure crystals of silicon, germanium, or other materials to which trace amounts of impurity atoms have been added so that they act as diodes

Types of detectors (cont.)

- Detectors may also be classified by the type of information produced:
  - Detectors, such as Geiger-Mueller (GM) detectors, that indicate the number of interactions occurring in the detector are called *counters*
  - Detectors that yield information about the energy distribution of the incident radiation, such as NaI scintillation detectors, are called *spectrometers*
  - Detectors that indicate the net amount of energy deposited in the detector by multiple interactions are called *dosimeters*

Modes of operation

- In *pulse mode*, the signal from each interaction is processed individually
- In *current mode*, the electrical signals from individual interactions are averaged together, forming a net current signal

Interaction rate

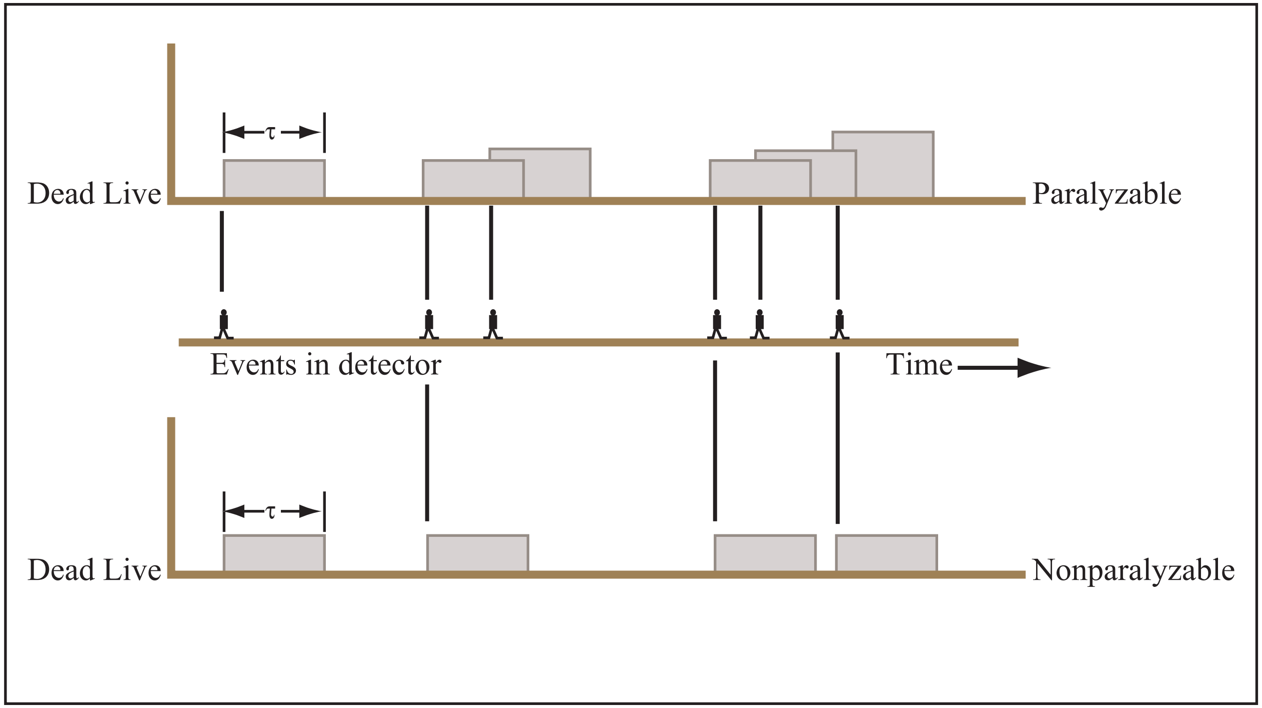
- Main problem with detectors in pulse mode is that two interactions must be separated by a finite amount of time if they are to produce distinct signals
  - This interval is called the *dead time* of the system
- If a second interaction occurs in this interval, its signal will be lost; if it occurs close enough to the first interaction, it may distort the signal from the first interaction
  - Show figure p.120

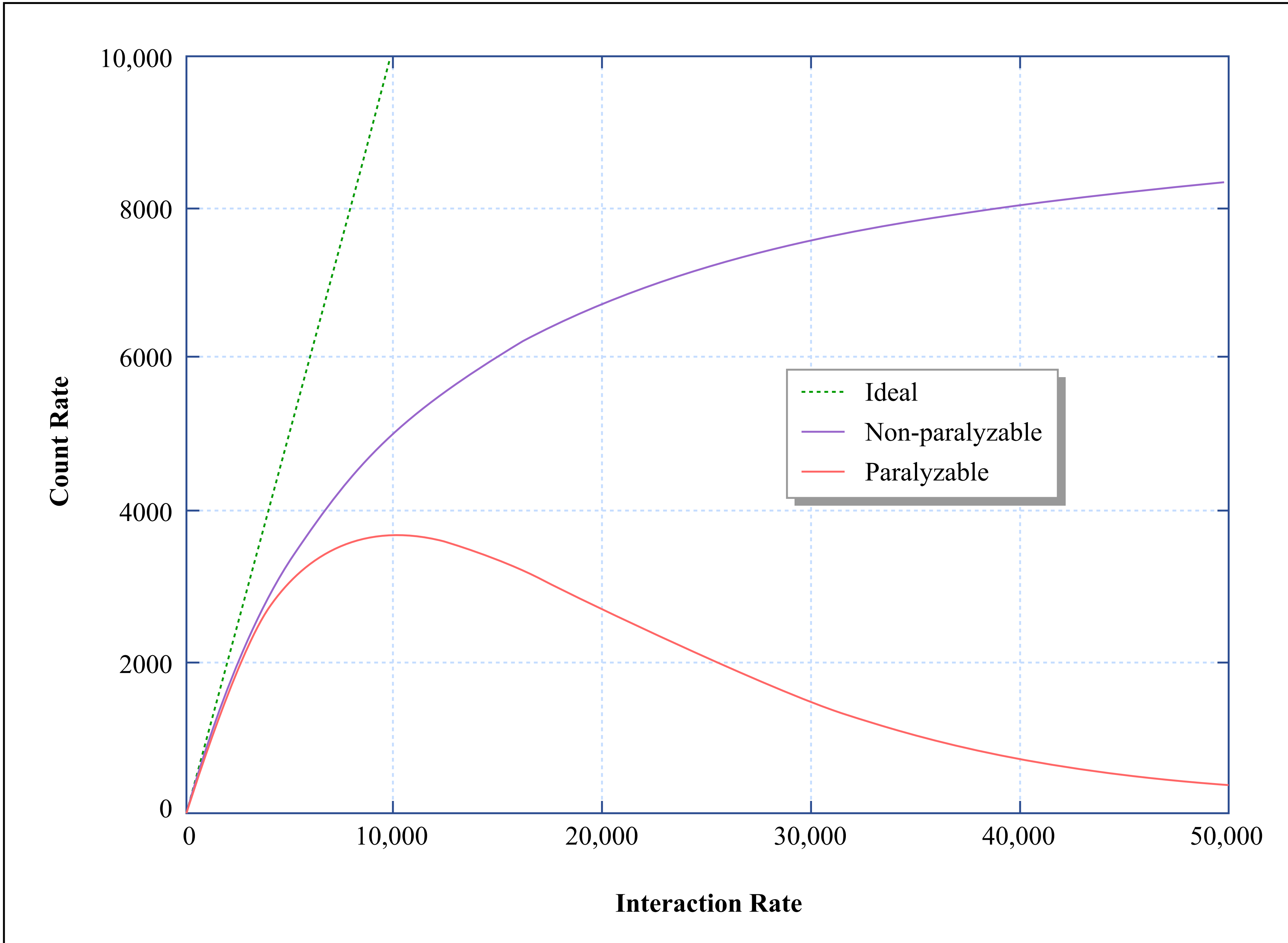
Dead time

- Dead time of a detector system largely determined by the component in the series with the longest dead time
  - Detector has longest dead time in GM counter systems
  - In multichannel analyzer systems the analog-to-digital converter often has the longest dead time
- GM counters have dead times ranging from tens to hundreds of microseconds, most other systems have dead times of less than a few microseconds

Paralyzable or nonparalyzable

- In a *paralyzable* system, an interaction that occurs during the dead time after a previous interaction extends the dead time
- In a *nonparalyzable* system, it does not
- At very high interaction rates, a paralyzable system will be unable to detect any interactions after the first, causing the detector to indicate a count rate of zero


τ
Dead Live
Paralyzable
Events in detector
Time
τ
Dead Live
Nonparalyzable



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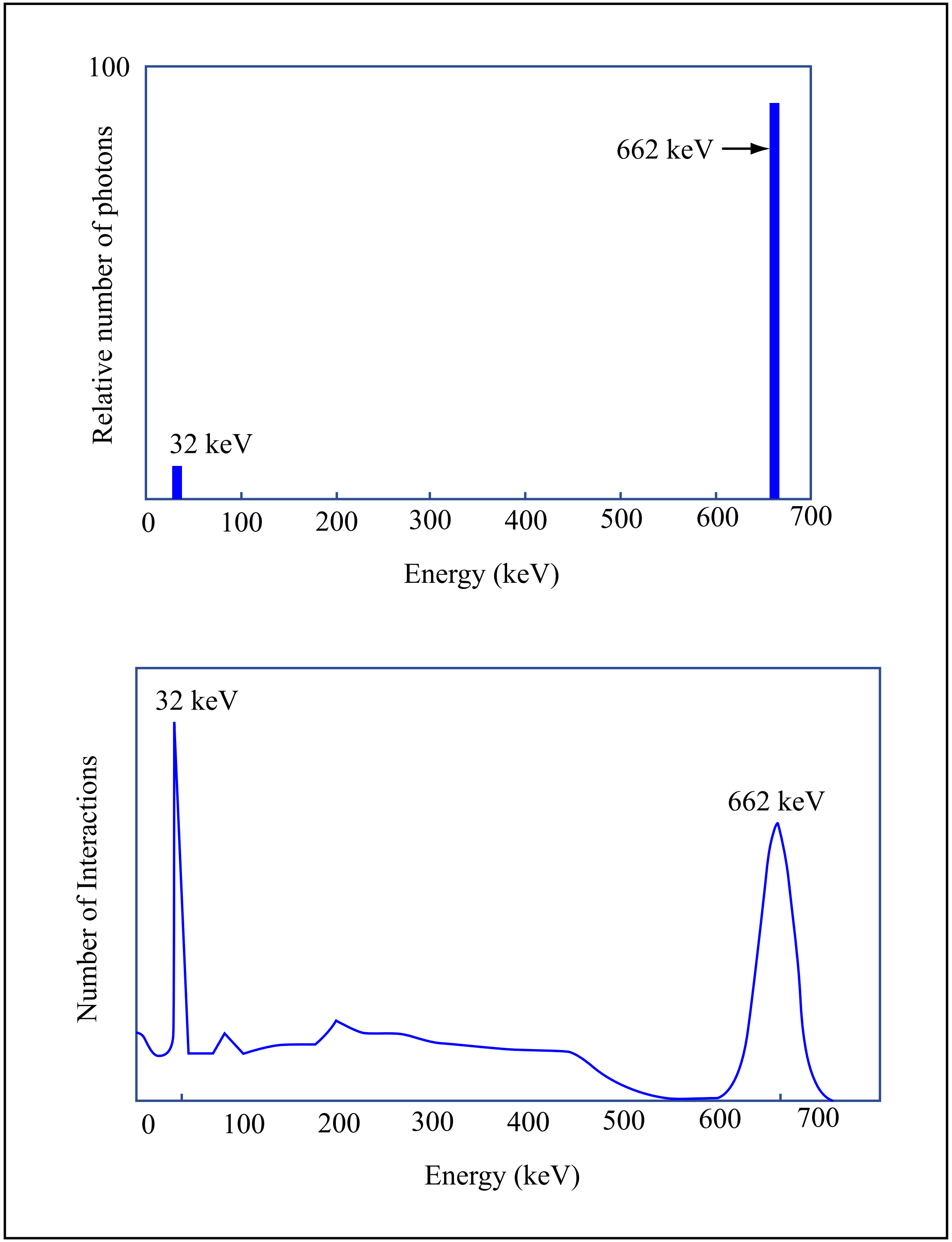
Current mode operation

- In current mode, all information regarding individual interactions is lost
- If the amount of 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

Spectroscopy

- 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*
- A *pulse height spectrum* is usually depicted as a graph of the number of interactions depositing a particular amount of energy in the spectrometer as a function of energy



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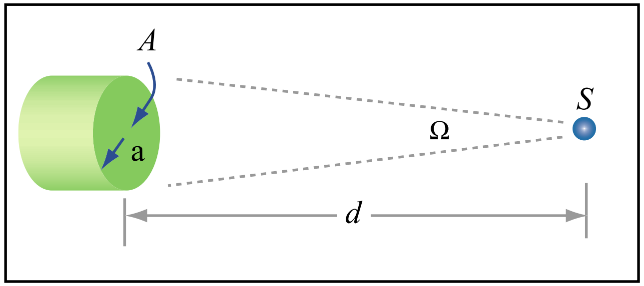
Detection efficiency

- 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

$$\text{Efficiency} = \frac{\text{Number detected}}{\text{Number emitted}}$$

$$\text{Efficiency} = \frac{\text{Number reaching detector}}{\text{Number emitted}} \times \frac{\text{Number detected}}{\text{Number reaching detector}}$$

$$\text{Efficiency} = \text{Geometric efficiency} \times \text{Intrinsic efficiency}$$



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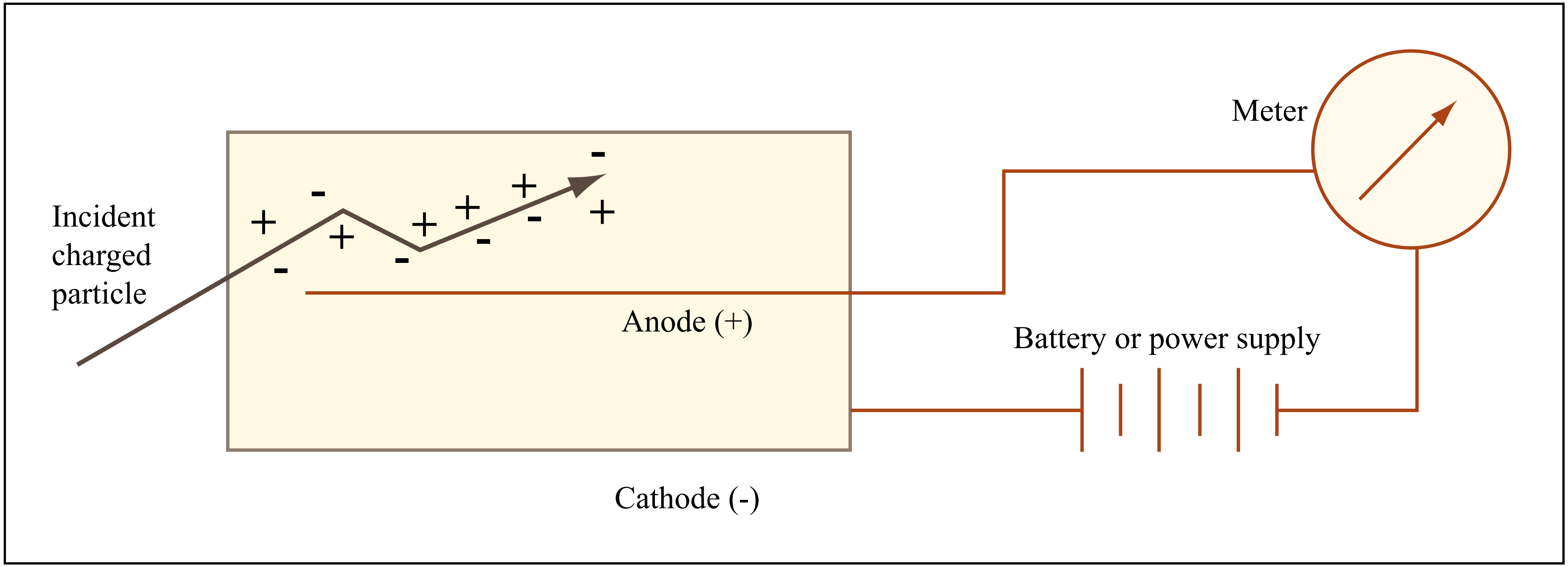
Gas-filled detectors

- A gas-filled detector consists of a volume of gas between two electrodes, with an electrical potential difference (voltage) applied between the electrodes
- Ionizing radiation produces ion pairs in the gas
- Positive ions (cations) attracted to negative electrode (cathode); electrons or anions attracted 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



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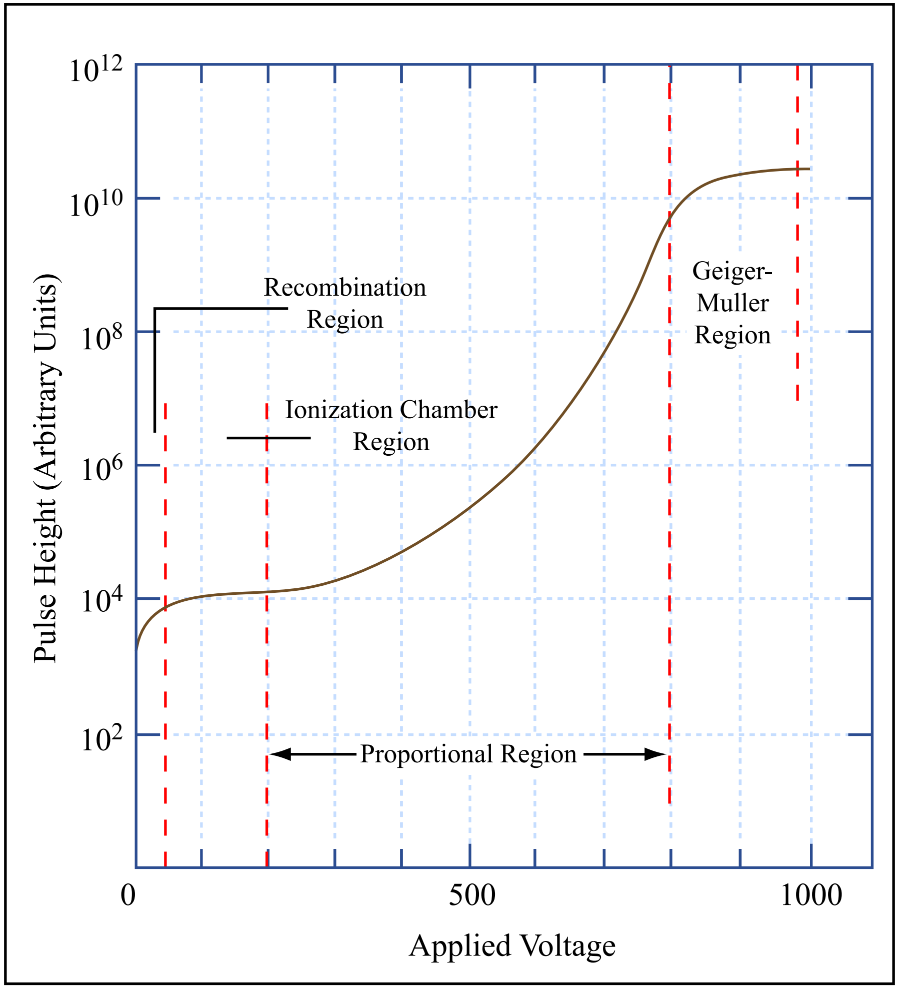
- Outer shell is a metal cylinder made of either Steel or Aluminum
  - Filled with a gas
- Inner wire is gold plated tungsten
  - Tungsten provides strength to the thin wire
  - Gold provides improved conductivity

Types of gas-filled detectors

- Three types of gas-filled detectors in common use:
  - Ionization chambers
  - Proportional counters
  - Geiger-Mueller (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

Ionization Counter

- Ionization region
  - All electrons are collected
  - Charge collected is proportional to the energy deposited
  - Called ion chambers



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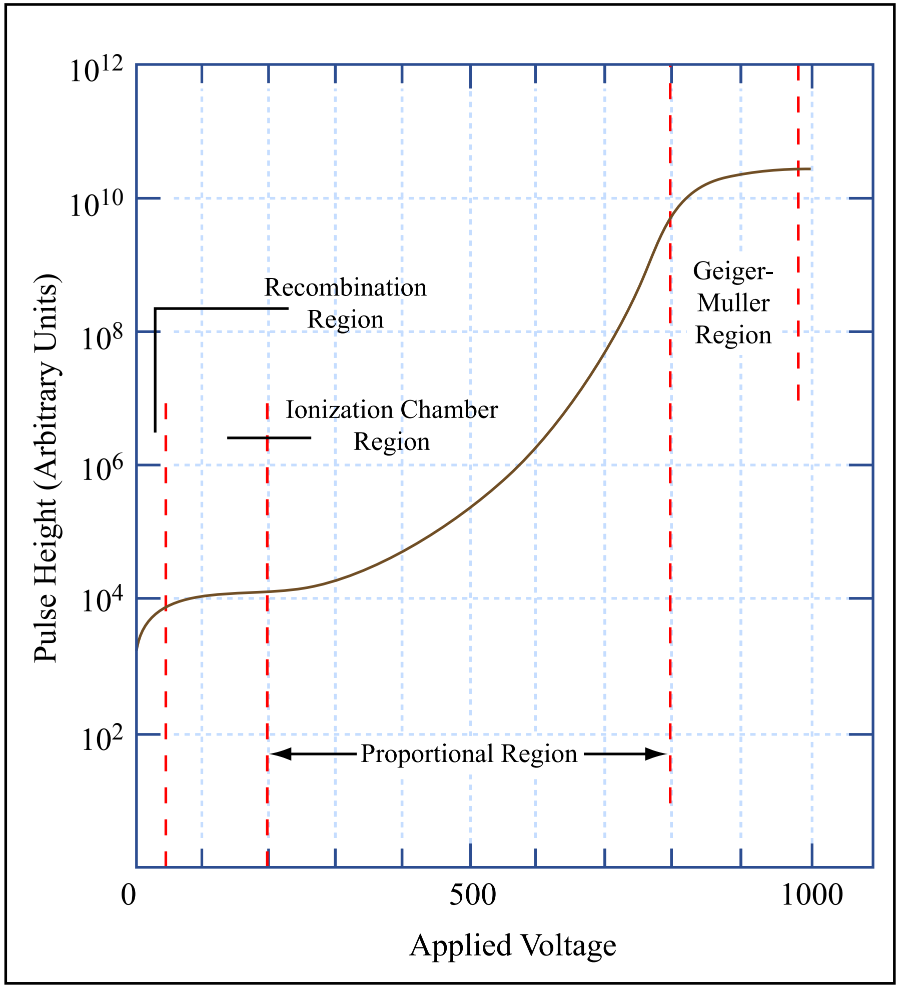
Ionization chambers

- 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

Proportional Counter

- Proportional region
  - Electric field is strong enough to create secondary ionization
  - Further increases create more ionization in the gas
    - Avalanche ionization
  - Charge collected is linearly proportional to energy deposited



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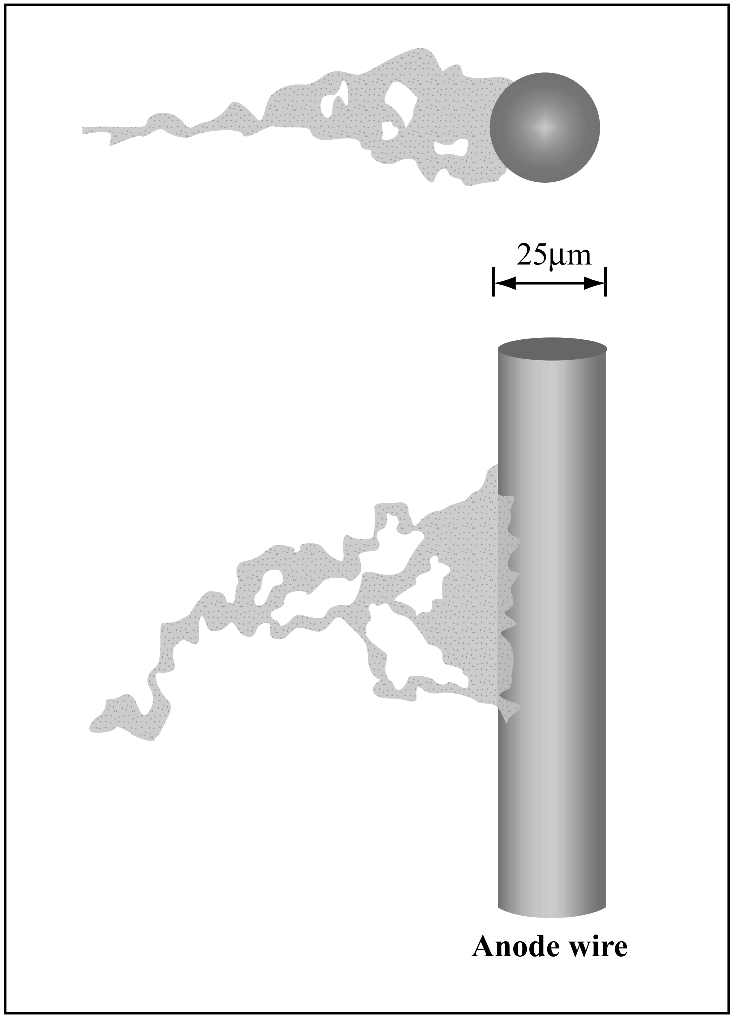
Avalanche Ionization



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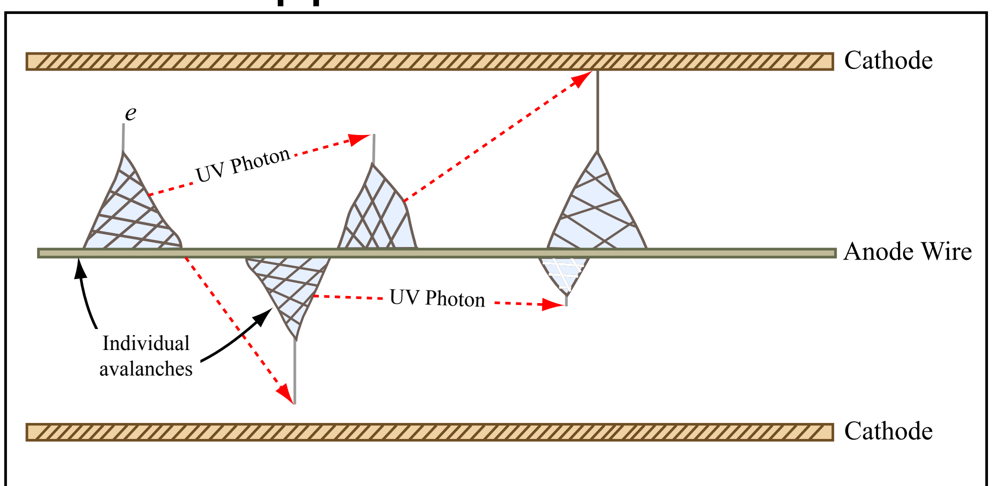
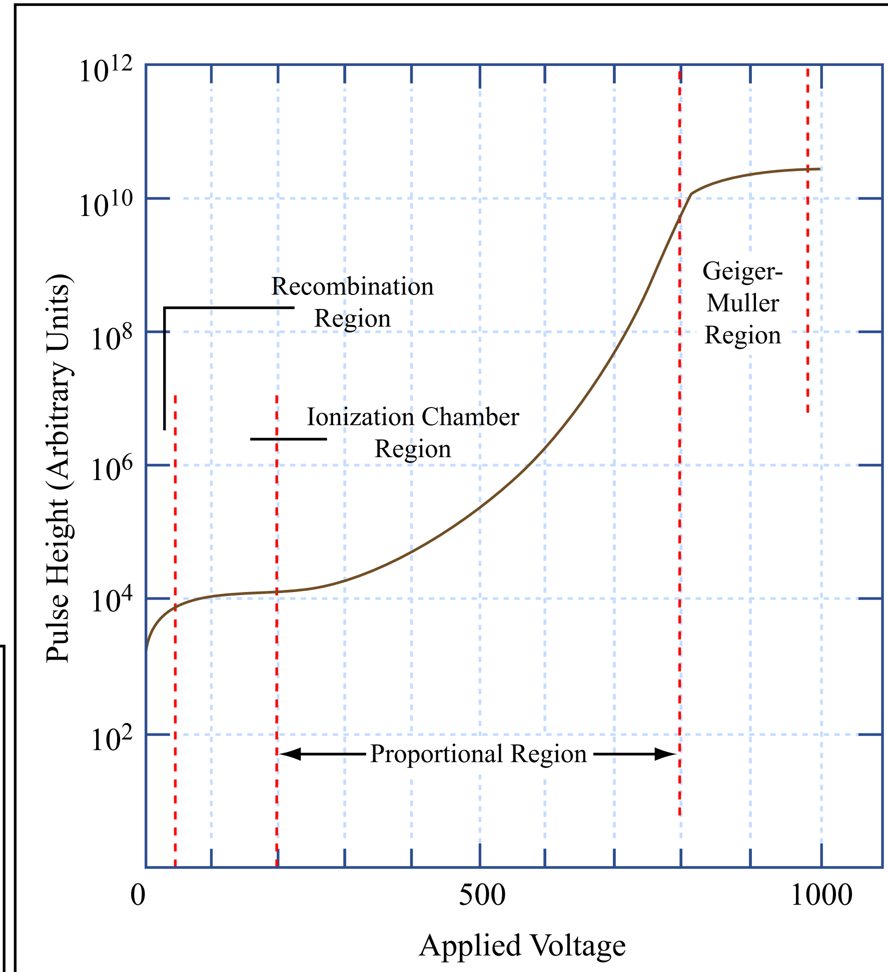
GM Counter

- Geiger-Mueller region
  - Saturation of the anode wire
  - Avalanche over the entire wire
  - Cannot be used for high count rate applications





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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 counters (cont.)

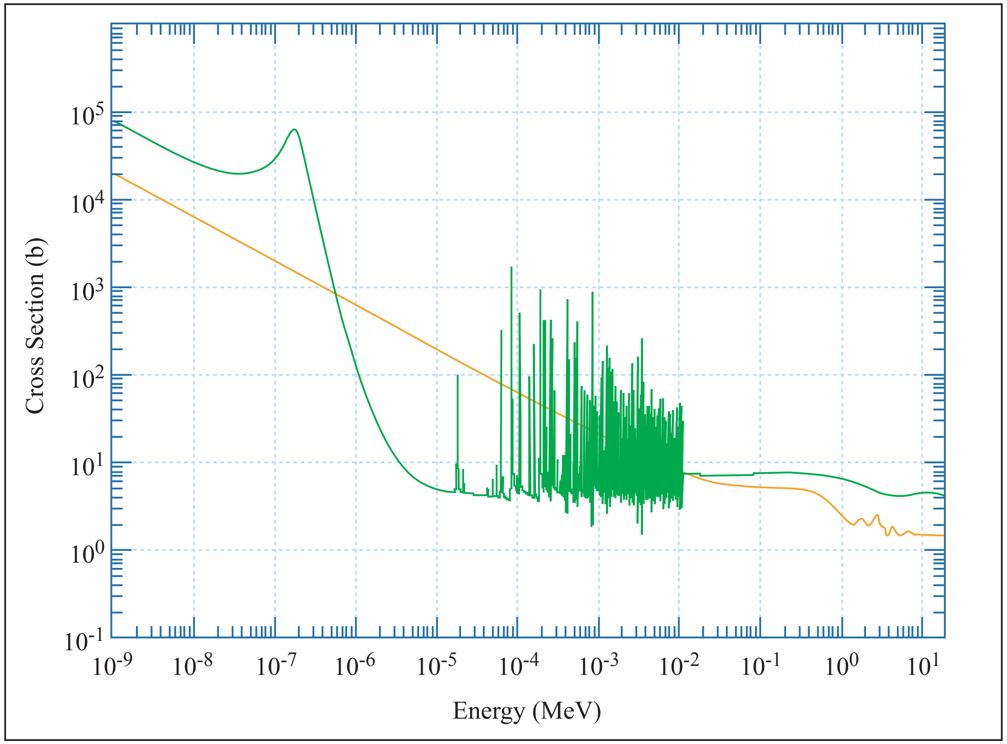
- GM detectors suffer from extremely long dead times – seldom used when accurate measurements are required of count rates greater than a few hundred counts per second
- Portable GM survey meter may become paralyzed in a very high radiation field – should always use ionization chamber instruments for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

Neutron Detection

- Neutral particles
  - Detection is based on indirect interactions
- Two basic interactions
  - Scattering
    - Recoiling nucleus ionizes surrounding material
    - Only effective with light nucleus (Hydrogen, Helium)
  - Nuclear reactions
    - Products of the reaction can be detected (gamma, proton, alpha, fission fragments)

Neutron Detection

- Since x.s. in most materials are strongly dependent on neutron energy, different techniques exist for different regions:
  - Slow neutrons (or thermal neutrons), below the Cadmium cutoff
  - Fast neutrons



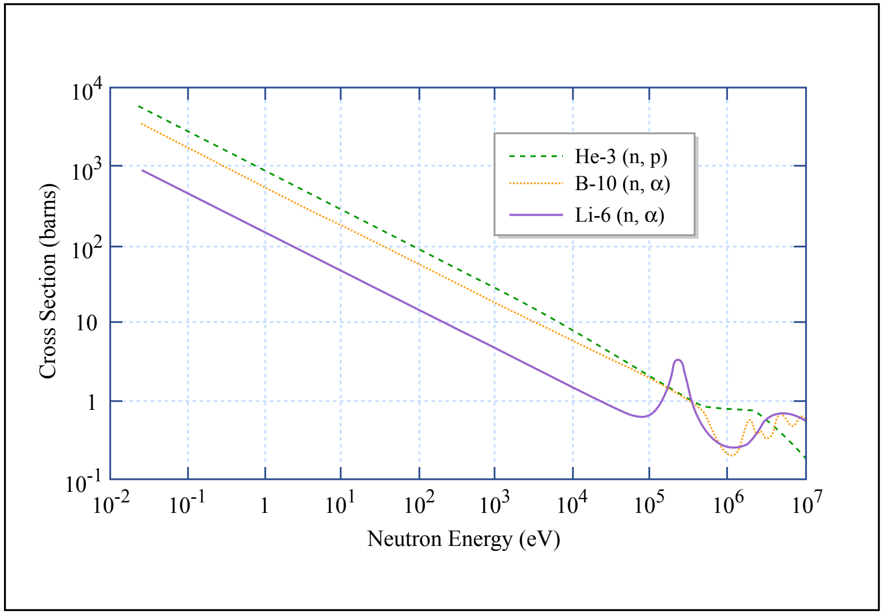
Thermal Neutron Detectors

- Two important aspects to consider
  - Find a material with large thermal x.s.
  - Find an arrangement that allows you to distinguish from gamma rays
    - High Q-value of neutron capture will make it easier

$^{3}He + n \rightarrow {}^{3}H + {}^{1}H + 765\ keV$

$^{10}B + n \rightarrow {}^{7}Li^{*} + {}^{4}He + 2310\ keV$

and $^{7}Li^{*} \rightarrow {}^{7}Li + 480\ keV$.



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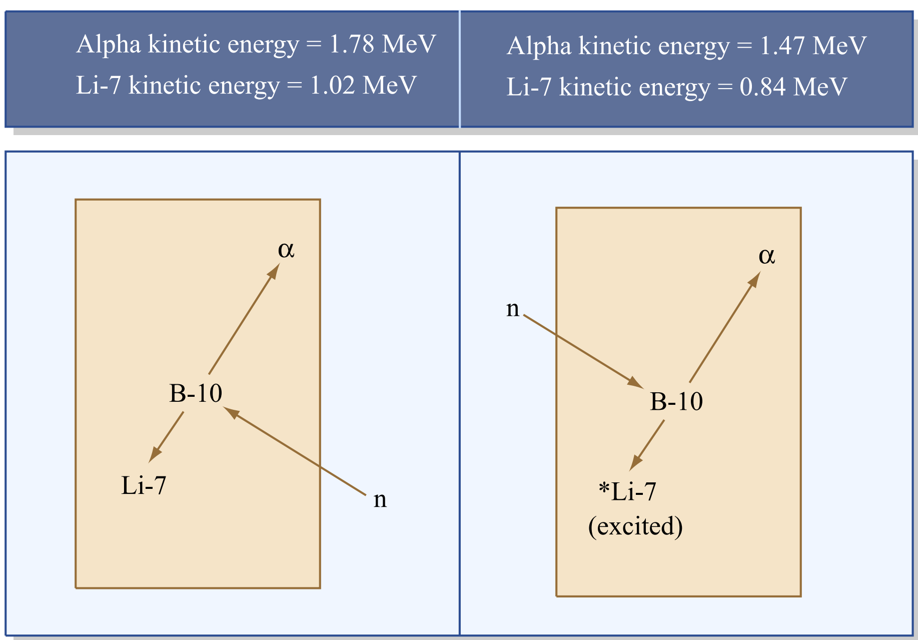
^{10}B(n,alpha)

- Equations
- 94% of the time in excited state
  - Q-value of 2.310 MeV
  - Other 6%, Q-value of 2.792 MeV



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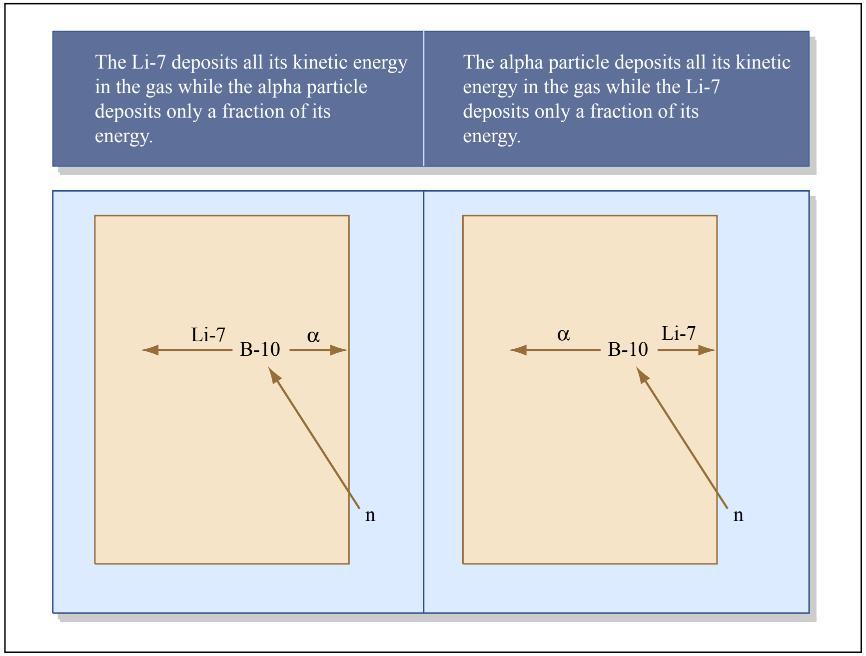
BF3 Tube



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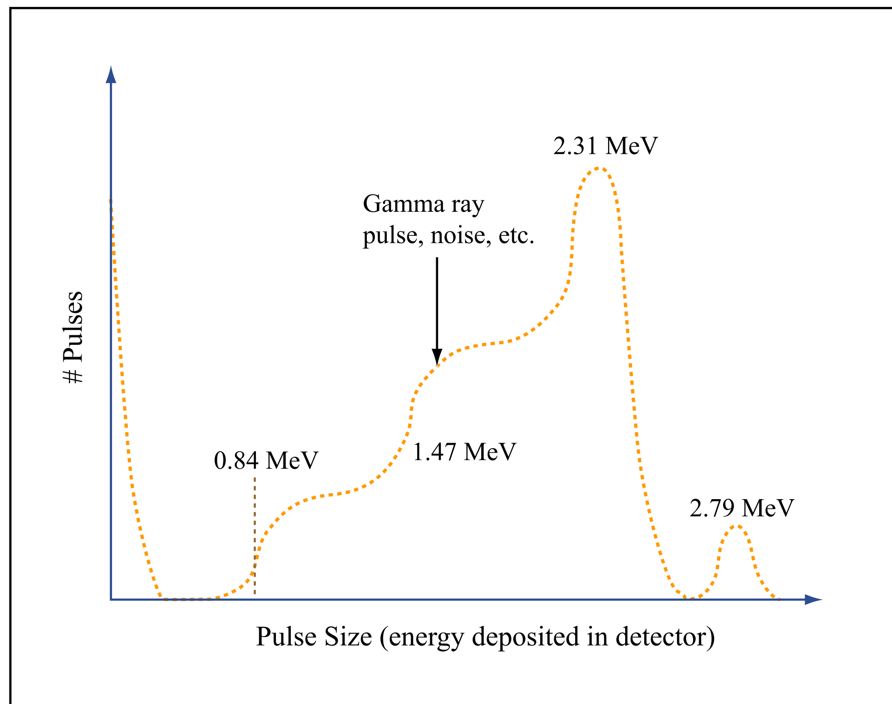

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Efficiency of BF3 Tube

- Intrinsic efficiency
  - Eff(E) = 1- exp(-Sigma(E) * L)

^{6}Li(n,alpha)

- Equation
- Only a ground state exists with Q-value of 4.78 MeV
  - $E_{He\text{-}3}$ = 2.73 MeV and E_{alpha} = 2.05 MeV

- Other possible reactions
  - ^{3}He(n,p)
  - ^{157}Gd

Gamma-ray sensitivity

Thermal Detectors	Interaction Probability	
	Thermal Neutron	1 - MeV Gamma Ray
^{3}He (2.5 cm diam, 4 atm)	0.77	0.0001
Ar (2.5 cm diam, 2 atm)	0.0	0.0005
BF_3 (5.0 cm diam, 0.66 atm)	0.29	0.0006
Al tube wall (0.8 mm)	0.0	0.014

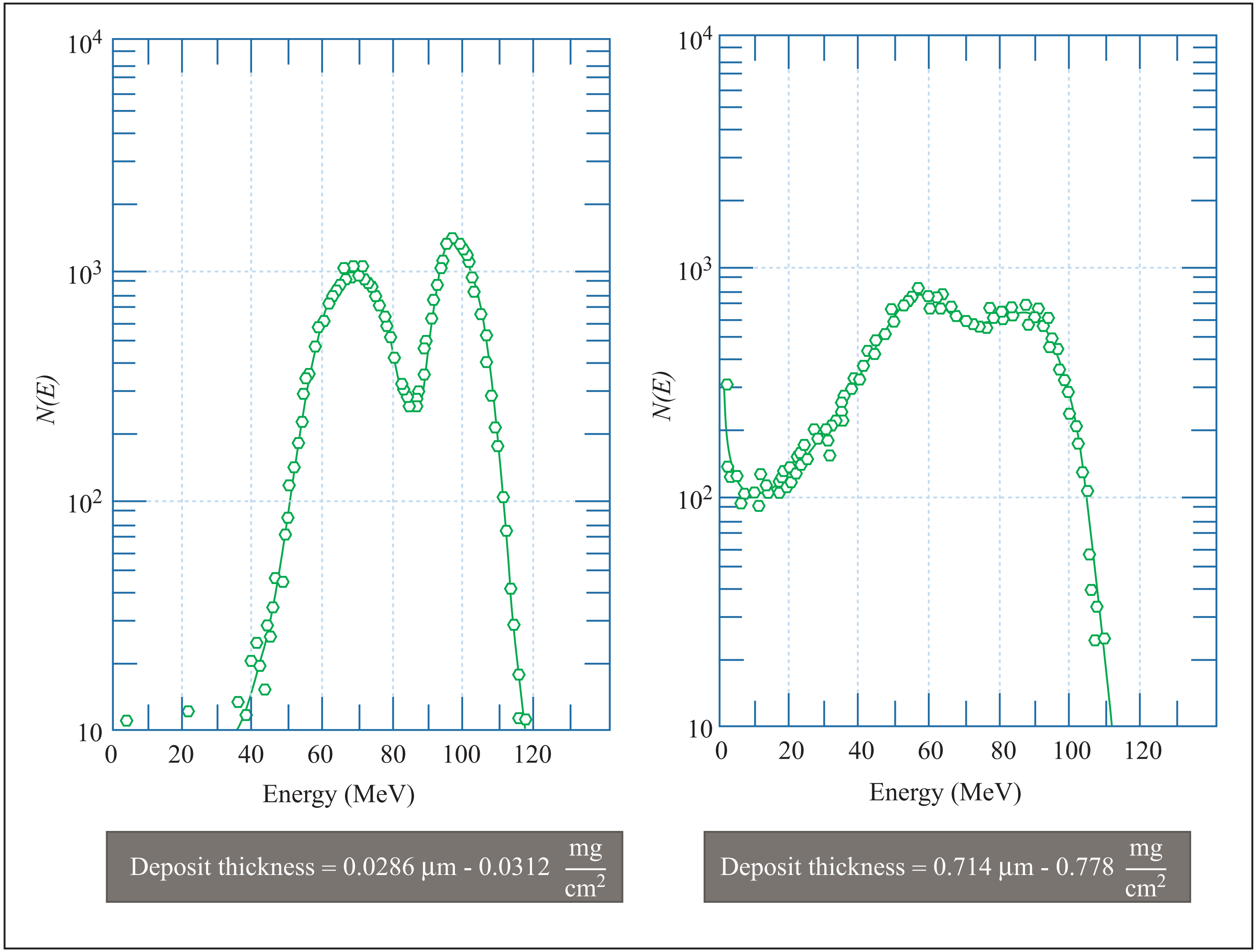
Fast Detectors	Interaction Probability	
	1 - MeV Neutron	1 - MeV Gamma Ray
^{4}He (5.0 cm diam, 18 atm)	0.01	0.001
Al tube wall (0.8 mm)	0.0	0.014
Scintillator (5.0 cm thick)	0.78	0.26

Neutron and gamma-ray interaction probabilities in typical gas proportional counters and scintillators

Fission chambers

- Inner surface of gas tube is coated with a fissile material (U-235)
  - Current mode in reactor operation
  - Pulse mode elsewhere
- Efficiency of about 0.5% at thermal energies
- Combine fissile and fertile material to avoid loss of sensitivity (regenerative chambers)
- Memory effect when used in high flux regions
  - Decay of FPs

Fission Chambers



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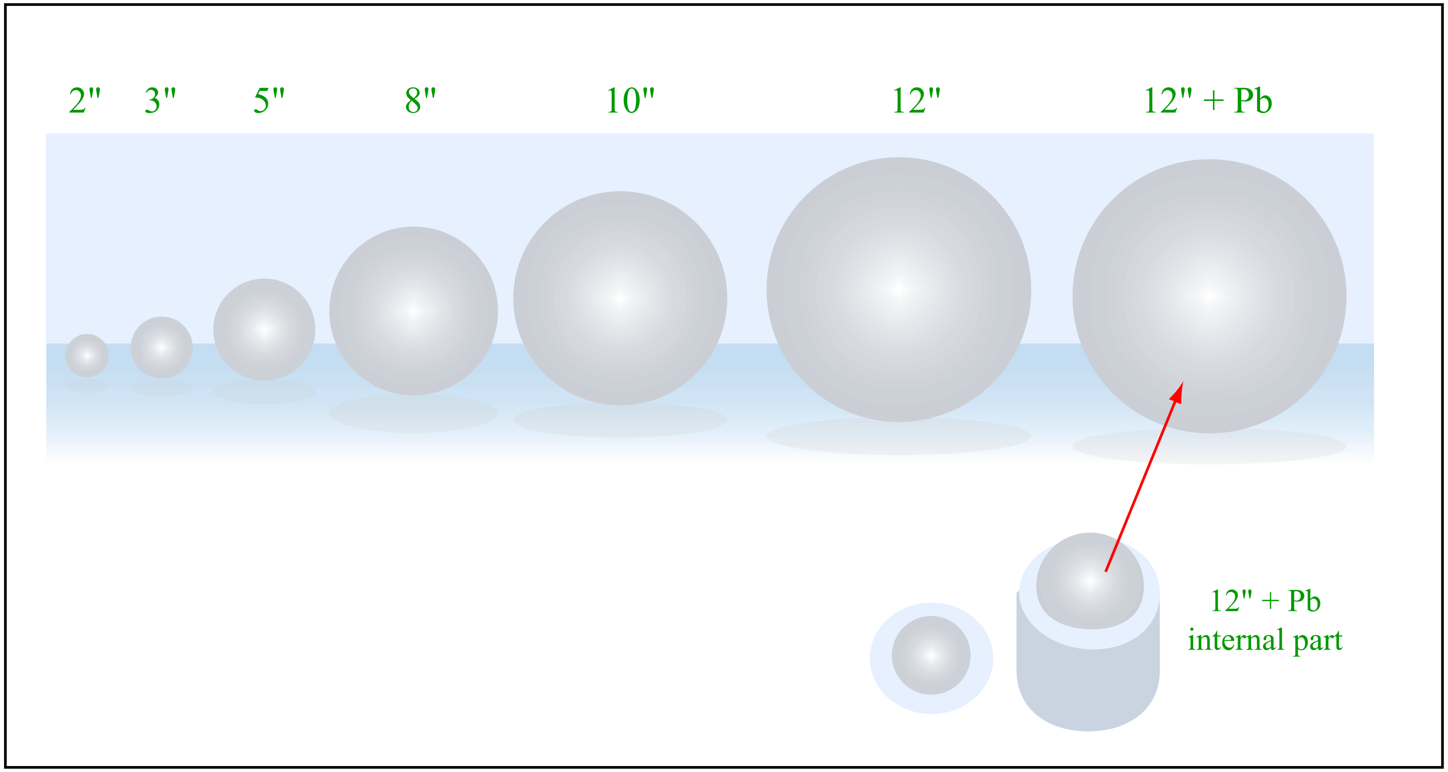
Neutron Spectroscopy

- Bonner Sphere



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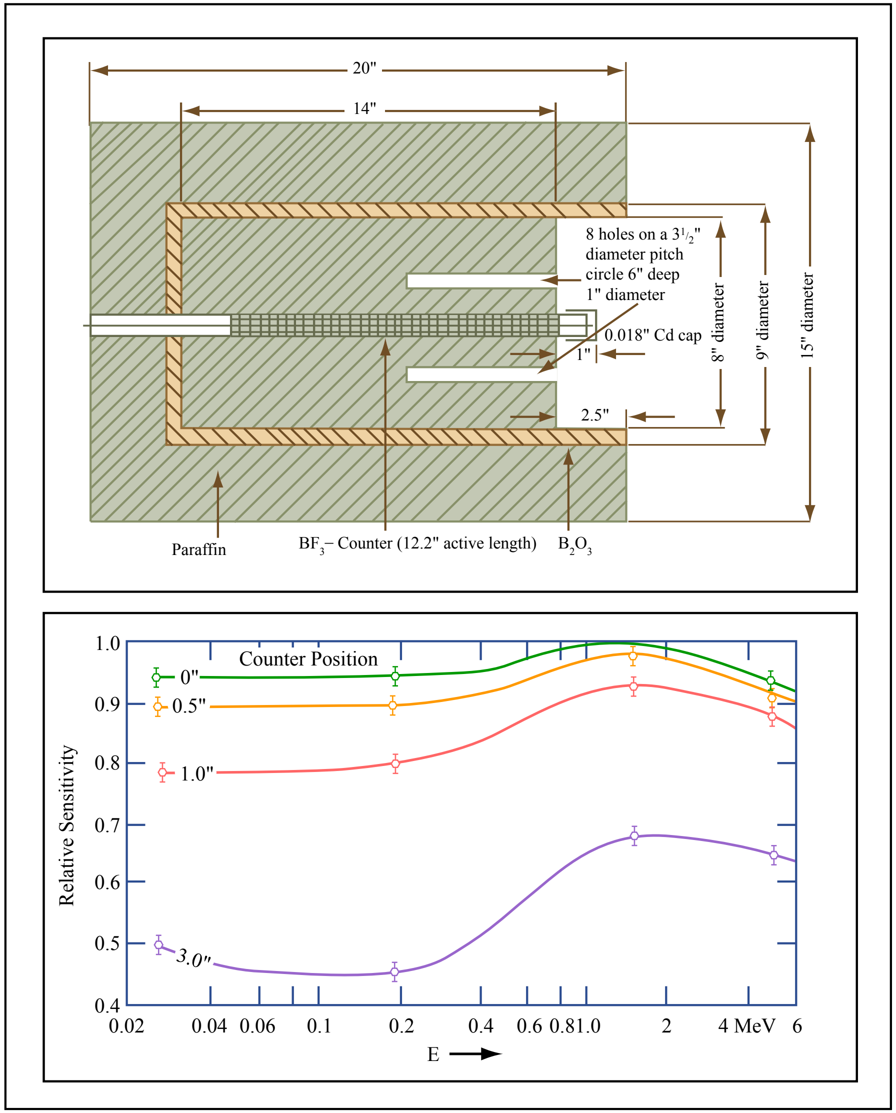
Long Counter

- Flat response for neutrons of all energy



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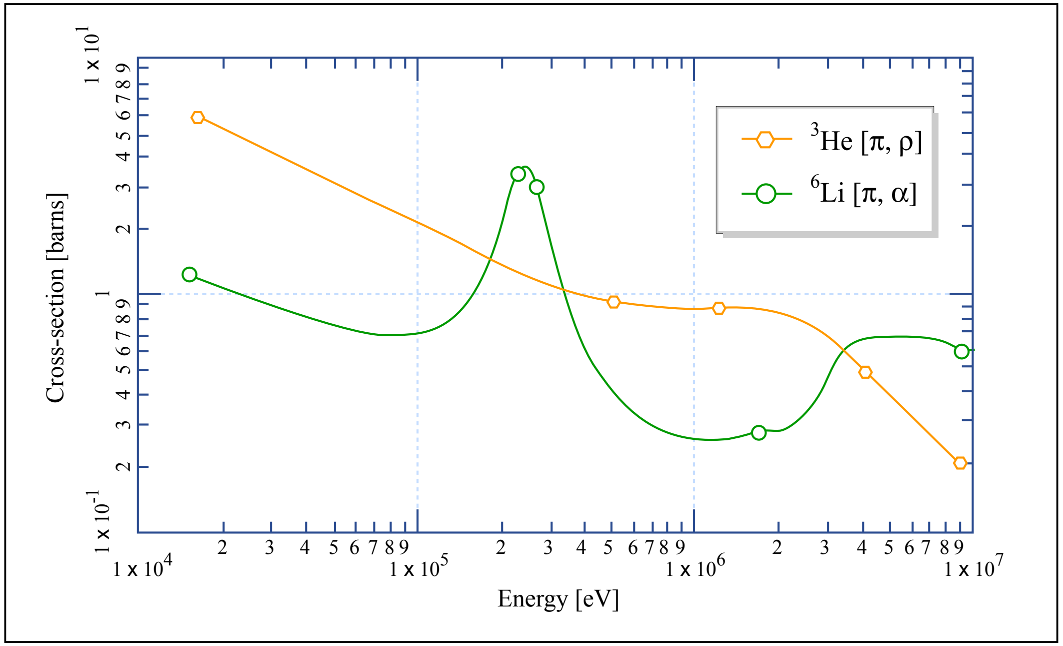
Fast-Neutron induced reaction detectors

- ^{6}Li(n,alpha)
  - Q-value of 4.78 MeV
  - Peaks appear at Q-value + neutron kinetic energy
  - Lithium based scintillators



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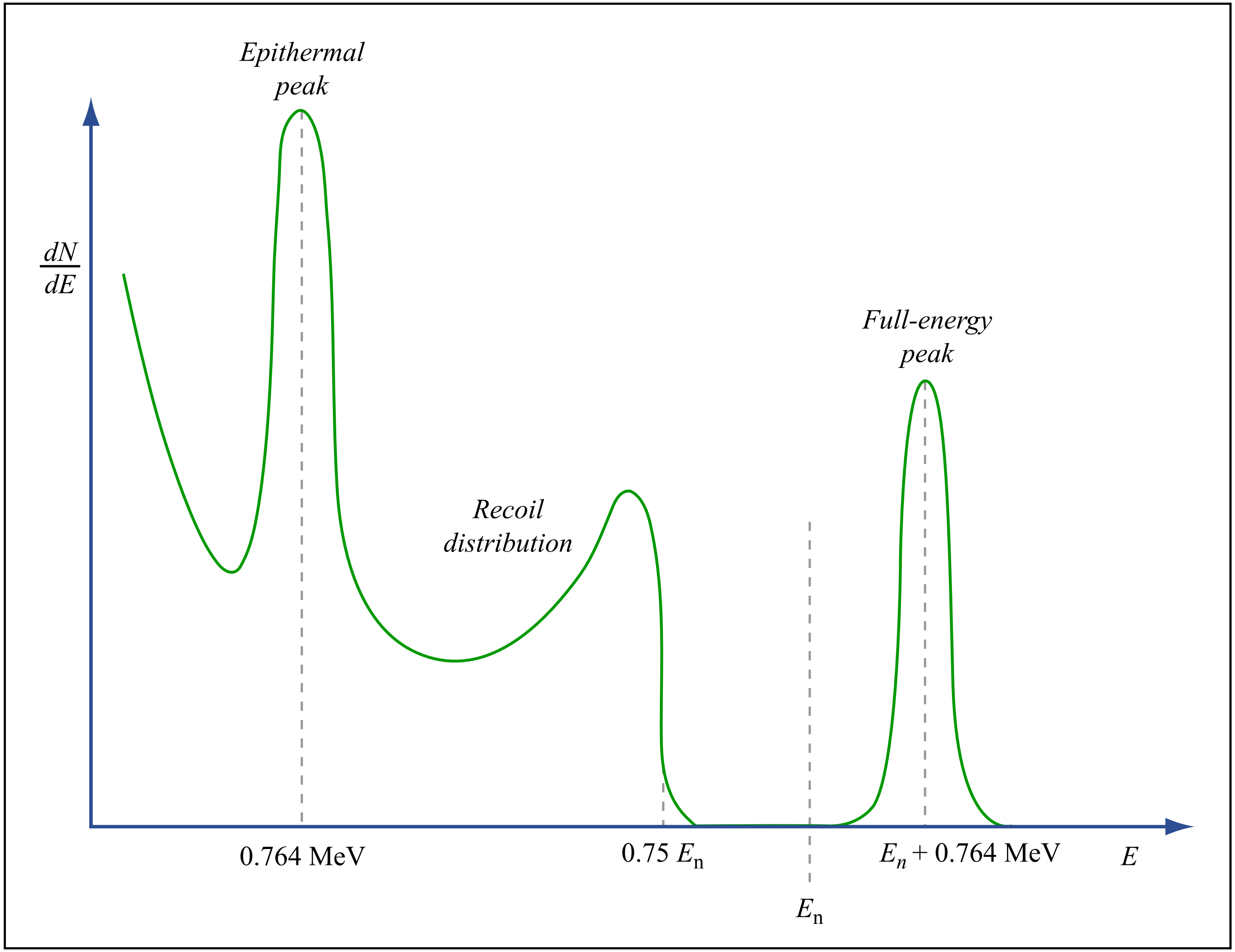
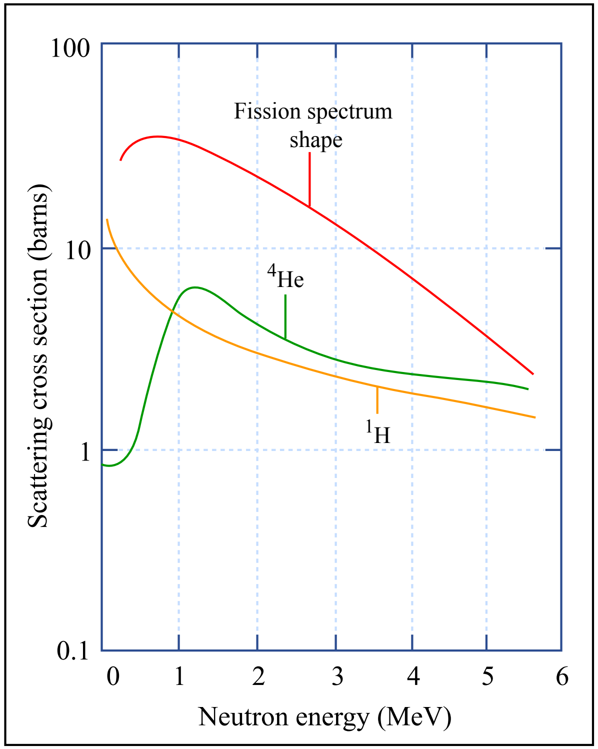
- $^{3}He(n,p)$
  - Energy range 20 keV to 2 MeV
    - Smooth, nearly flat x.s.
    - Tube is wrapped in Cadmium and Boron layersto reduce contribution from thermal neutrons
    - Lead shield is also added to reduce impact of photons
    - Intrinsic efficiency is very low (0.1%)
    - Full energy peak at En + 765 keV
    - Thermal neutron capture peak at 765 keV
    - Elastic scattering spectrum with a max at 0.75En



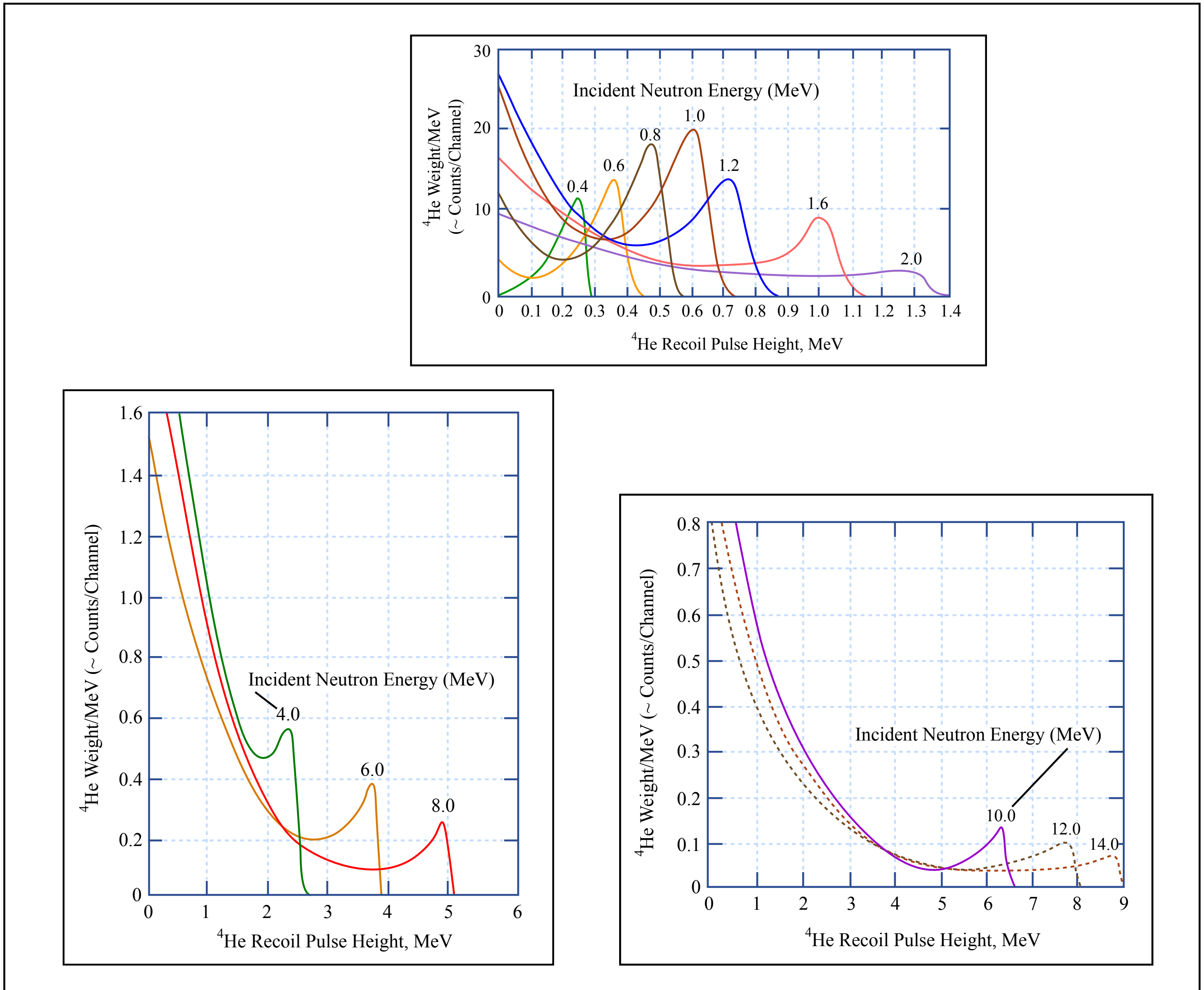
Epithermal
peak
dN
dE
Full-energy
peak
Recoil
distribution
0.764 MeV
0.75 En
En + 0.764 MeV
E
En

Fast Neutron Recoil Detectors

- Most useful reaction is elastic scattering
  - Recoil nucleus will ionize medium
  - Most popular target is hydrogen
    - Large elastic scattering x.s
    - Well known x.s.
    - Neutron can transfer all of its energy in one collision
  - Q-value is zero
    - Information can be found about the incoming neutron energy



Gas recoil detectors



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Scintillators

- Desirable properties:
  - High conversion efficiency
  - Decay times of excited states should be short
  - Material transparent to its own emissions
  - Color of emitted light should match spectral sensitivity of the light receptor
  - For x-ray and gamma-ray detectors, μ should be large – high detection efficiencies
  - Rugged, unaffected by moisture, and inexpensive to manufacture

Scintillators (cont.)

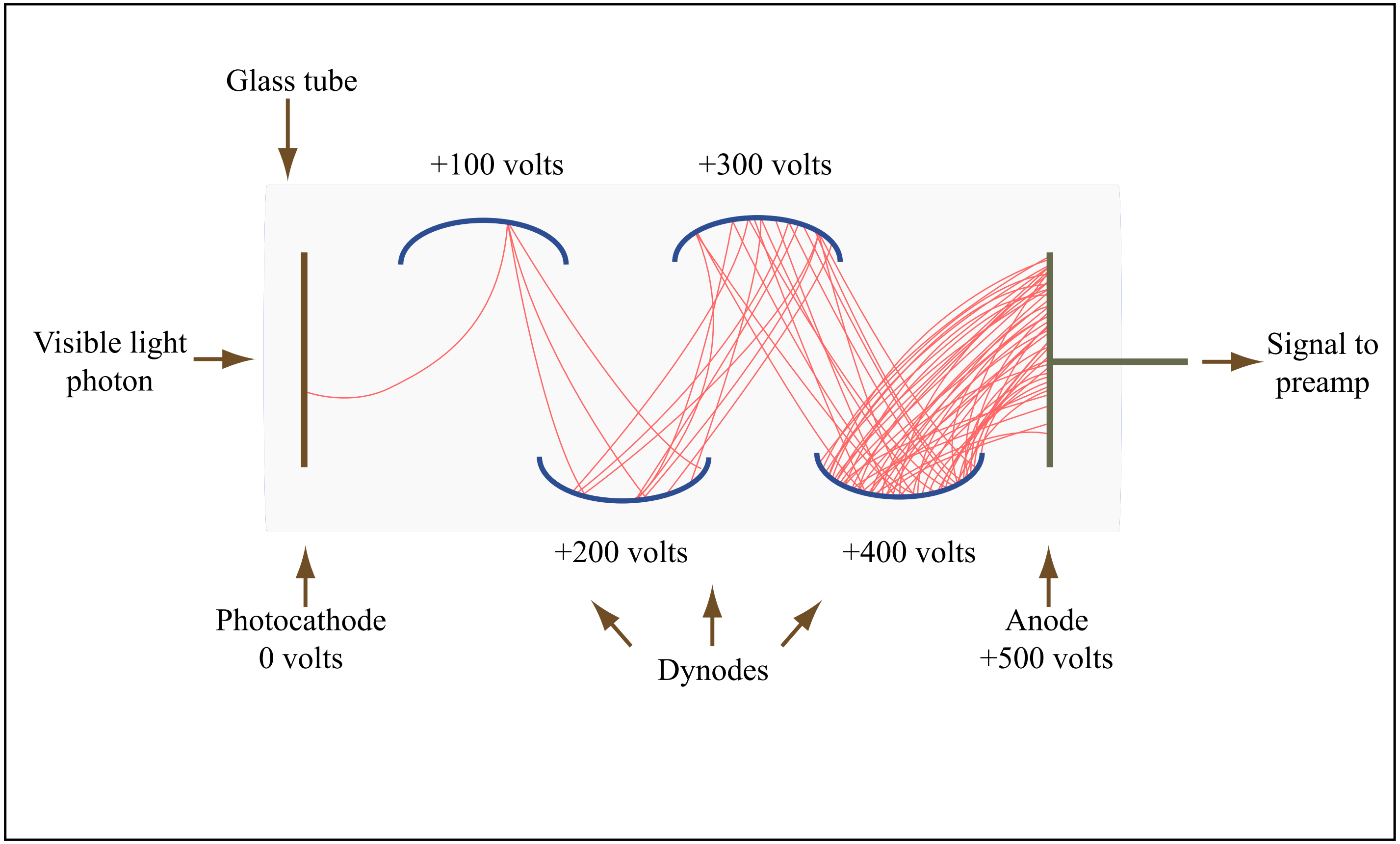
- Amount of light emitted after an interaction increases with energy deposited by the interaction
- May be operated in pulse mode as spectrometers
- High conversion efficiency produces superior energy resolution

Materials

- Sodium iodide activated with thallium [NaI(Tl)], coupled to PMTs and operated in pulse mode, is used for most nuclear medicine applications
  - Fragile and hygroscopic
- Bismuth germanate (BGO) is coupled to PMTs and used in pulse mode as detectors in most PET scanners

Photomultiplier tubes

- PMTs perform two functions:
  - Conversion of ultraviolet and visible light photons into an electrical signal
  - Signal amplification, on the order of millions to billions
- Consists of an evacuated glass tube containing a photocathode, typically 10 to 12 electrodes called dynodes, and an anode


Glass tube
+100 volts
+300 volts
Visible light photon
Signal to preamp
+200 volts
+400 volts
Photocathode
0 volts
Dynodes
Anode
+500 volts

Dynodes

- Electrons emitted by the photocathode are attracted to the first dynode and are accelerated to kinetic energies equal to the potential difference between the photocathode and the first dynode
- When these electrons strike the first dynode, about 5 electrons are ejected from the dynode for each electron hitting it
- These electrons are attracted to the second dynode, and so on, finally reaching the anode

PMT amplification

- Total amplification of the PMT is the product of the individual amplifications at each dynode
- If a PMT has ten dynodes and the amplification at each stage is 5, the total amplification will be approximately 10,000,000
- Amplification can be adjusted by changing the voltage applied to the PMT