Chapter 6: Basic radiation detectors

Set of 60 slides based on the chapter authored by
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Nuclear Medicine Physics:
A Handbook for Teachers and Students

Objective: To familiarize the student with the fundamental concepts of basic radiation detectors

Slide set prepared in 2015
by J. Schwartz (New York, NY, USA)

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CHAPTER 6 TABLE OF CONTENTS

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6.1. INTRODUCTION

6.1.1. Radiation detectors — complexity and relevance

- Radiation detectors are of paramount importance in nuclear medicine

- The detectors provide a wide range of information including:
  - Radiation dose of a laboratory worker
  - Positron emission tomography (PET) image of a patient

- Consequently, detectors with strongly differing specifications are used

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6.1. INTRODUCTION

6.1.2. Interaction mechanisms, signal formation and detector type

- ☐ Radiation detectors
  - Sensors that produce signals upon interaction with radiation
  - Signals can be processed electronically to give requested information
- ☐ X-rays & γ-rays interaction mechanisms
  - Photoelectric effect
  - Compton scattering
  - Pair production
  - Relative importance depends on
    - Radiation energy
    - Interaction medium
  - Result in production of energetic electrons
    - These will eventually transfer their energy to interaction medium by ionization and excitation

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6.1. INTRODUCTION

6.1.2. Interaction mechanisms, signal formation and detector type

- Charged particles transfer their energy by ionization & excitation
- Ionization results in
  - Charge carriers production:
    - Electrons and ions in a gaseous detection medium
    - Electrons and holes in a semiconductor material
    - Light quanta emission in scintillators
- Radiation detectors
  - Charge or current forms signal
  - Signal created by charge motion in applied electric field
    - Gas filled detectors
    - Semiconductor detectors
  - Light emission observed using light sensor that produces charge or current
    - Scintillation detectors

6.1. INTRODUCTION

6.1.3. Counting, current, integrating mode

- Radiology / radiotherapy radiation detectors
  - Operated in current mode
  - Intensities too high for individual counting of events
- Nuclear medicine
  - Primarily use counting mode
  - Energy information
  - Arrival time information
- Personal dosimeters
  - Detector used in integrating mode
  - Dose is measured monthly
  - Information extracted much later after actual interaction

6.1. INTRODUCTION

6.1.4. Detector requirements

☐ Radiation detector quality expressed in terms of

- Sensitivity
- Energy resolution
- Time and position resolution
- Counting rate performance

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6.1. INTRODUCTION

6.1.4. Detector requirements

6.1.4.1. Sensitivity

☐ Sensitivity depends on

- Subtended solid angle
- Detector efficiency for radiation interaction
  - Relevant energy range is ~30–511 keV, where it's governed by:
    - Photoelectric effect
      - Attenuation length (cm) ~ ρZ_{eff}^{3-4}

        ρ = density, Z_{eff} = effective atomic number of the compound
    - Compton scattering
      - Almost independent of Z
      - Proportional to ρ
  - ρ of gas-filled detector is 3 orders of magnitude smaller than for solid state detector
  - Need highest possible ρ and Z_{eff} at 511 keV

6.1. INTRODUCTION

6.1.4. Detector requirements

6.1.4.2. Energy, time and position resolution

☐ Energy resolution

- Strongly coupled to number of information carriers
- Number of information carriers
  - Given by $N = E/W$
    - E = Radiation energy
    - W = Mean energy needed to produce information carrier
  - Largest number produced in semiconductors
  - Smallest number produced in inorganic scintillators + PMT’s

6.1. INTRODUCTION

6.1.4. Detector requirements

6.1.4.2. Energy, time and position resolution

- Mean energies *W* to produce information carriers

Detector type	*W* (eV)
Gas filled (electron–ion)	30
Semiconductor (electron–hole)	3
Inorganic scintillator (light quantum)	25
Inorganic scintillator + PMT (electron)	100
Inorganic scintillator + Si diode (electron–hole pair)	35

6.1. INTRODUCTION

6.1.4. Detector requirements

6.1.4.2. Energy, time and position resolution

- ☐ Energy resolution definition:

$$\frac{\Delta E}{E} = \frac{\Delta N}{N} = 2.35\sqrt{\frac{FW}{E}}$$

- ΔE = FWHM
- $N = E/W$
- $\Delta N = 2.35\sigma$
- $\sigma^2 = FN$
- F = Fano factor

➢ Gas-filled detectors	$F = 0.05–0.20$
➢ Semiconductors	$F \approx 0.12$
➢ Scintillator	$F = 1$

6.1. INTRODUCTION

6.1.4. Detector requirements

6.1.4.2. Energy, time and position resolution

- Time resolution
  - Mainly important for PET in nuclear medicine
  - Time resolution depends on 2 main factors
    - Rise time of the signal pulses
    - Height of the signal pulses
      - Important because there is also noise
      - Easier to determine pulse position when the pulse is higher relative to noise
      - Time jitter due to pulse height (energy) variation is less important
  - Inorganic Scintillators detectors preferred because they have
    - Fast response
    - Fast rise time
    - Light sensors’ fast response

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6.1. INTRODUCTION
6.1.4. Detector requirements
6.1.4.2. Energy, time and position resolution

☐ Position resolution

- Most easily obtained by pixelating detector at pitch corresponding to requested resolution
- In nuclear medicine, important in:
  - Gamma camera /SPECT
  - PET detection systems
    - Use of monolithic scintillator blocks recently studied
      - Light detection by pixelated sensors
      - Analogous to gamma camera
      - Broad light distribution measured using pixels smaller than centre of the distribution
      - Resolution better than the pixel size

6.1. INTRODUCTION

6.1.4. Detector requirements

6.1.4.3. Counting rate and dead time

- Achievable counting rate depends on
  - Detector response time
    - Time to transport charge carriers to form signal
    - Time to emit the scintillation light
  - Time needed to process the signals
  - Time needed to handle the data

6.1.4.3. Counting rate and dead time

Dead time (DT): Minimum time between true events at which these are counted separately

☐ Non-paralysable detectors

- Second event $t < \tau$ ⇨ Not counted
- Second event $t > \tau$ ⇨ Counted
- DT fixed at τ

$$R = \frac{T}{1 + T\tau}$$

- T = true event rate
- R = counting rate
- $R\tau$ = Fraction of time system is dead
- $TR\tau$ = rate of loss of events = $T - R$

6.1. INTRODUCTION

6.1.4. Detector requirements

6.1.4.3. Counting rate and dead time

- Paralysable detectors
  - Second event $t < \tau$ ⇨ not counted
    - DT extended τ from time of second event
  - 3rd event at $t > \tau$ after 1st event & within τ after 2nd event ⇨ not counted
    - DT extended another τ
  - DT is not fixed
    - Can become $\gg \tau$
    - i.e. 'extendable' dead time
  - Counted: event which occurs at $t > \tau$
  - Counting rate = rate of occurrences of time intervals > τ between events

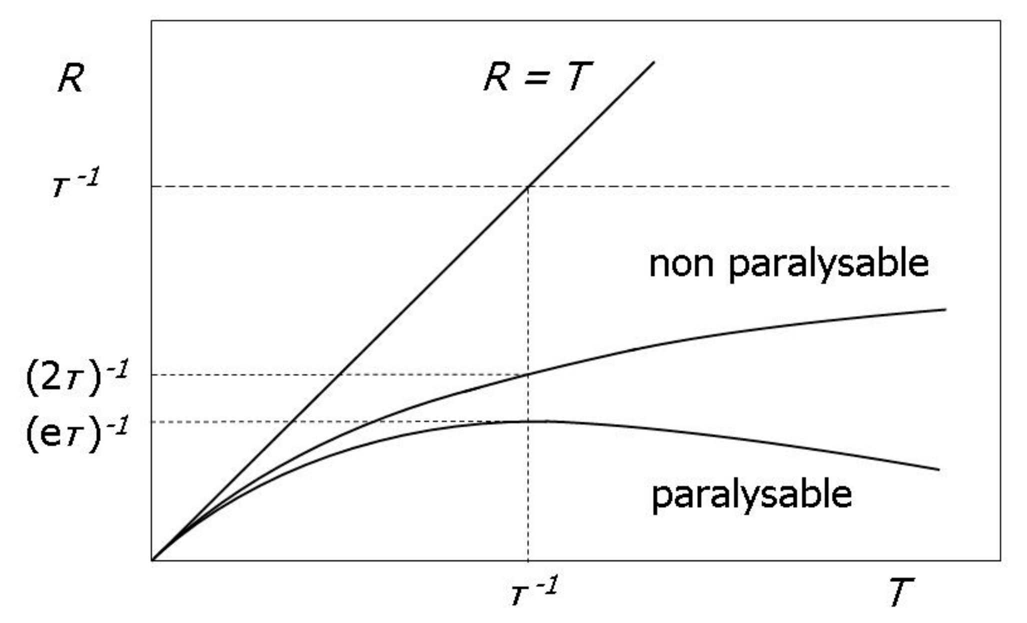
$$R = Te^{-T\tau}$$

6.1. INTRODUCTION

6.1.4. Detector requirements

6.1.4.3. Counting rate and dead time

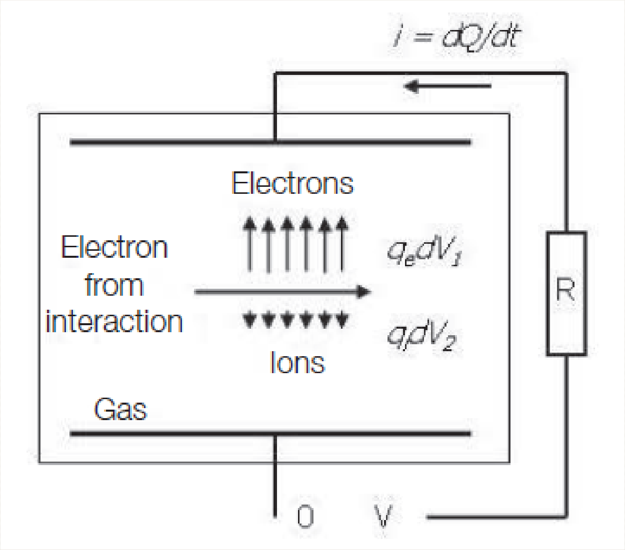
- Relation between *R* and *T* for
  - non-paralysable and paralysable cases
  - if $\tau = 0$, than $R = T$



6.2. GAS FILLED DETECTORS

6.2.1. Basic principles

- ❑ Energetic electrons
  - Produce secondary electrons travelling through gas
  - Secondary electrons drift to anode & ions to cathode



The mode of operation depends on applied voltage (*V*)

6.2. GAS FILLED DETECTORS

6.2.1. Basic principles

- Relatively low *V*
  - Recombination region
  - Produces weak electric field *E*
  - *E* too weak to efficiently separate the (-) and (+) charges
  - Some will recombine
  - Full signal not observed

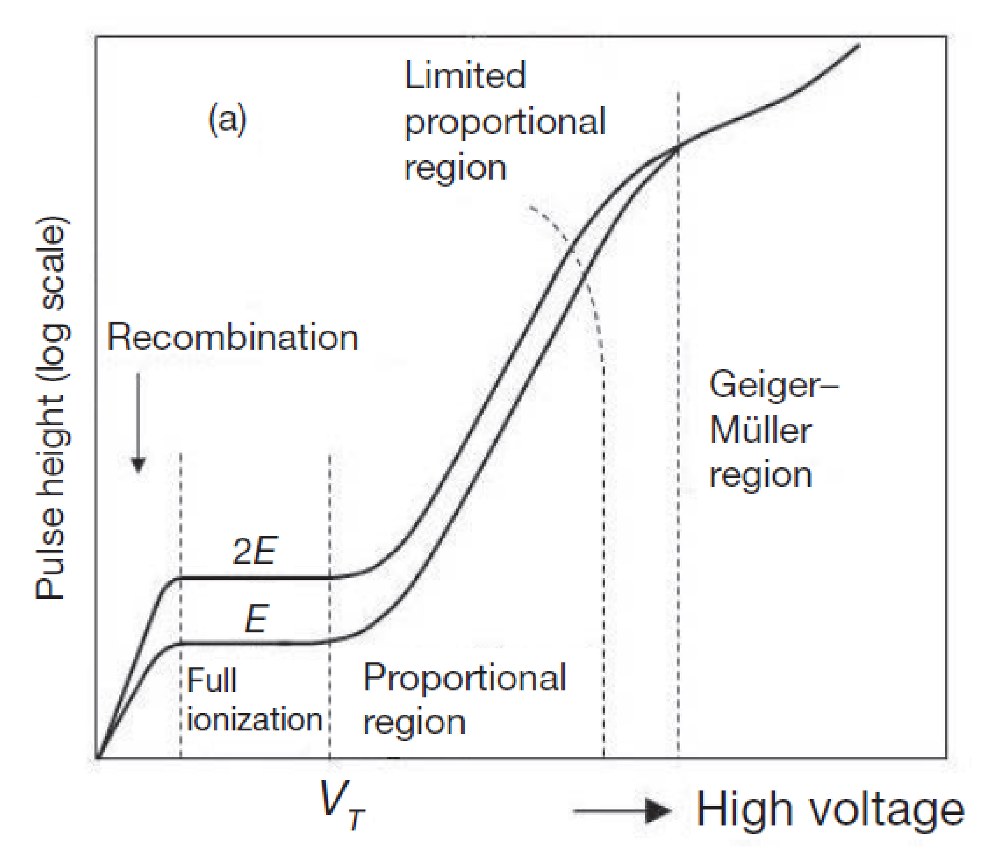
  Increasing *V* decreases recombination

- Relatively high voltage *V*
  - Full ionization
  - Heavier charged particles & higher rates→ higher *V*
  - Signal becomes constant over wide *V* range
  - Typical operating *V* of ionization chamber: 500 to 1000 V

6.2. GAS FILLED DETECTORS

6.2.1. Basic principles

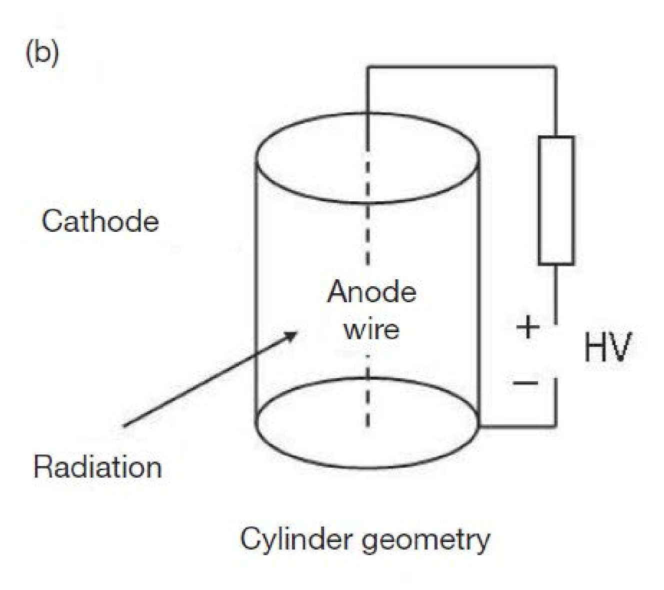
- Pulse height as a function of applied high *V* for gas filled detectors



6.2. GAS FILLED DETECTORS

6.2.1. Basic principles

- Operation at stronger electric field *E*
  - Examples:
    - cylindrical detector geometry
    - thin anode wire in centre
    - metal cylinder as cathode
  - $E(r)$ □ V/r
  - At V_T = threshold voltage
    - *E* near anode
      - Very strong
      - Drifting electron gains enough energy to ionize gas atom
    - Proportional region
      - For gain $M \approx 10^4$, *M* is independent of deposited energy
      - proportional counter
    - At normal temperature and pressure $E_T \approx 10^6$ V/m.
      - For parallel plate geometry with depth ~1 cm, $V_T \approx 10$ kV → not practicable
    - Due to the r^{-1} dependence manageable *V* can be applied for proportional operation (1–3 kV)



Cylinder geometry

6.2. GAS FILLED DETECTORS

6.2.1. Basic principles

☐ Operation at stronger electric field *E*

- At further increased *V*
  - Space charge effects start to reduce effective *E*
  - Affect the gain
  - Process will start at lower *V* for higher primary ionization density events
- Limited proportionality region is entered
- At further increased *V*
  - Pulse height will become independent of the deposited energy
- Geiger–Müller region is entered
- *V* further increased
  - Ionization zone expands
  - Avalanche & significant amplification obtained

6.2. GAS FILLED DETECTORS

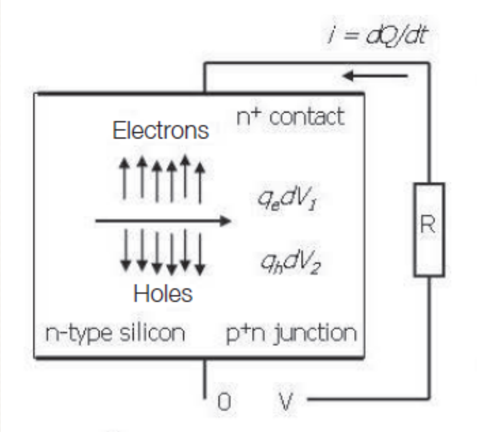
6.2.1. Basic principles

- ☐ Multi-wire proportional chamber (MWPC)
  - Alternate geometry
  - Many equidistant parallel anode wires
    - Pitch of 1–2 mm
    - Positioned in a plane inside a box
    - Walls are cathode planes
  - Employed in autoradiography
  - Micro-patterned detectors made with photo-lithography
    - Operate analogously to the MWPC
    - *Examples:*
      - Micro-strip gas chamber
      - Gas electron multiplier
      - Spatial resolutions are of the order of 0.1 mm

6.3. SEMICONDUCTOR DETECTORS

6.3.1. Basic principles

- ☐ Semiconductor detector is a capacitor
  - After interaction
    - Electrons lifted from valence into conduction band
      - ➢ Charge carriers transported in applied electric field
  - Applying voltage difference to electrodes on opposite sides of a slab of semiconductor leads to a current that’s too high for practical use as detector
  - At room temperature,
    - Electrons are lifted from valence to conduction band by thermal excitation due to small gap ($E_{gap} \approx 1$ eV)
    - Free electrons and holes cause a current
      - ⇨ Make into a diode and operate in reverse bias



6.3. SEMICONDUCTOR DETECTORS

6.3.1. Basic principles

- *Example*: Silicon
  - Semiconductor-electronics used to make diode structure
  - N-type silicon
    - Doped with electron-donor impurities
    - Reduces number of holes
    - Electrons are the majority charge carriers
  - P-type silicon
    - Doped with electron-acceptor impurities
    - Strongly reduces number of free electrons
    - Holes are the majority charge carriers

6.3. SEMICONDUCTOR DETECTORS

6.3.1. Basic principles

- *Example*: Silicon
  - Junction diode
    - Formed when n-type brought into contact with p-type material
    - Depletion region
      - Space charge zone results at junction
      - Due to diffusion of majority charge carriers
    - Reverse-biased
      - Positive voltage applied on n-type side with respect to p-type side
      - Depletion layer thickness increased
      - High enough voltage fully depletes layer
        - No free charge carriers left
        - Virtually no current flows
        - Only small current remains (leakage or dark current)

6.3. SEMICONDUCTOR DETECTORS

6.3.1. Basic principles

- *Example*: Silicon
  - Diode
    - n-type doped with impurities in narrow zone
      - makes p^+ n junction
      - p^+**:** high doping concentration
    - Use high-purity Si & blocking contact for further leakage current reduction
      - n^+ doping at n-type side
    - If the leakage current is still problematic, the temperature can be decreased
    - Use of high purity semiconductor material is important for reducing leakage current
      - Energy levels in the gap may trap charge carriers resulting from the interaction with radiation and the energy resolution of a detector would be reduced

6.3. SEMICONDUCTOR DETECTORS

6.3.1. Basic principles

- *Example:* Silicon → Other approaches to make a detector
  - Start with p-type material and make n$^+$p junction diode
  - Apply a combination of surface oxidation and deposition of thin metal layer
    - Called surface barrier contacts
  - For thicknesses <1 mm it's possible to use intrinsic Si with p$^+$ & n$^+$ blocking contacts on opposite sides (p–i–n configuration)
  - For thicker detectors impurities are compensated for by introducing interstitial Li ions
    - Use slightly p-type intrinsic Si
    - Li ions act as electron donors
    - Li ions can be drifted ~10 mm
  - For large enough band gap metal contacts will suffice

6.3. SEMICONDUCTOR DETECTORS

6.3.1. Basic principles

- Important parameters of electrons and holes
  - Mobilities: μ_e and μ_h
  - Lifetimes: τ_e and τ_h
  - Drift velocity $\upsilon_{e,h}$ in electric field *E*
  - The path length a charge carrier can travel in its lifetime is given by:

$$\upsilon_{\mathrm{e,h}}\tau_{\mathrm{e,h}} = \mu_{\mathrm{e,h}}\tau_{\mathrm{e,h}}E$$

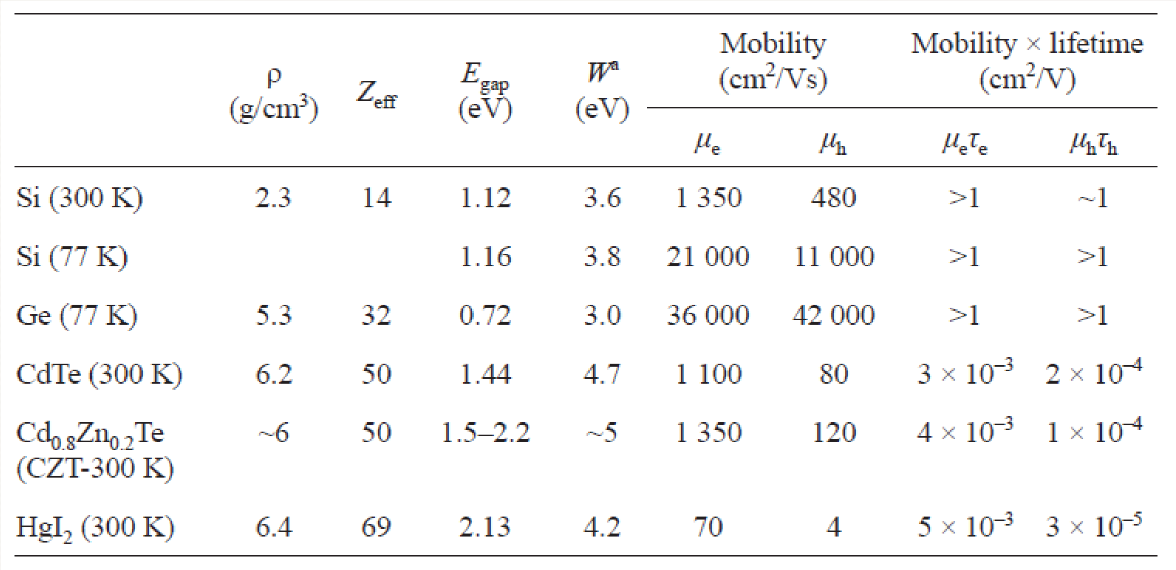
  - Mobilities for a given detector size and *E*
    - Provide drift times of charge carriers
    - Provide signal formation times
  - Mobilities & lifetimes are related to the probability that charge carriers arrive at collecting electrodes

6.3. SEMICONDUCTOR DETECTORS

6.3.2. Semiconductor detectors

❑ Semiconductor properties relevant for nuclear medicine

- Density ρ
- Z_{eff} for photoelectric effect
- E_{gap} and W value
- $\mu_{e,h}$ and their products with lifetimes
- Si primarily of interest for (position sensitive) detection of low energy X rays, beta particles and light quanta



	ρ (g/cm^3)	Z_{eff}	E_{gap} (eV)	W^a (eV)	Mobility (cm^2/Vs)		Mobility × lifetime (cm^2/V)	
					μ_e	μ_h	$\mu_e\tau_e$	$\mu_h\tau_h$
Si (300 K)	2.3	14	1.12	3.6	1 350	480	>1	~1
Si (77 K)			1.16	3.8	21 000	11 000	>1	>1
Ge (77 K)	5.3	32	0.72	3.0	36 000	42 000	>1	>1
CdTe (300 K)	6.2	50	1.44	4.7	1 100	80	3×10^{-3}	2×10^{-4}
$Cd_{0.8}Zn_{0.2}Te$ (CZT-300 K)	~6	50	1.5–2.2	~5	1 350	120	4×10^{-3}	1×10^{-4}
HgI_2 (300 K)	6.4	69	2.13	4.2	70	4	5×10^{-3}	3×10^{-5}

6.3. SEMICONDUCTOR DETECTORS

6.3.2. Semiconductor detectors

- ☐ Detection of X-rays of 300 eV - 60 keV
  - Si(Li)
    - Commercially available planar circular Li drifted p–i–n
    - Thickness up to 5mm
    - Diameters 4–20 mm
    - For typical *E*=1000 V/cm drift times to electrodes are on the order of tens of ns
    - Energy resolutions (FWHM) at 5.9 keV are 130–220 eV at 77 K
  - Position sensitive Si detectors commercially available with a large variety of pixel structures
  - Si detectors also used in personal dosimeters

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6.3. SEMICONDUCTOR DETECTORS

6.3.2. Semiconductor detectors

☐ High resolution gamma-ray spectroscopy uses Ge detectors

- Higher density & Z
- Made of high purity material
- Large volume detectors in coaxial geometry
  - Made of cylindrical crystals with core removed
  - High purity n-type or p-type used with corresponding junction
  - Contacts on outside and blocking contacts on inside
  - Operated at 77 K
- Commercially available cylindrical detectors
  - Diameter ≤ 10 cm, height ≤ 10 cm
- Drift times to electrodes ≤ 100 ns
- Typical energy resolutions
  - 1 keV at 122 keV γ-ray energy
  - 2 keV at 1332 keV γ-ray energy

6.3. SEMICONDUCTOR DETECTORS

6.3.2. Semiconductor detectors

☐ CdTe (cadmium telluride) and CZT (cadmium zinc telluride)

- Z is significantly higher than for Ge
- Possible to operate at room temperature due to larger band gap
- High purity n-type or p-type material is used
- Worse energy resolution than Ge
  - e.g. 2.5% FWHM at 662 keV (primarily due to relatively short lifetime of holes, resulting in incomplete charge collection)
- To observe the electron signal only use either or both:
  - Electronic correction techniques
  - Detectors with special electrode configurations (small pixels or grids)
- Dimensions: ~ 25 × 25 × 10 mm^3
- 16 × 16 pixels detectors are available
- e.g. used for SPECT innovation

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6.3. SEMICONDUCTOR DETECTORS

6.3.2. Semiconductor detectors

- HgI$_2$ (mercury iodide) is attractive for efficient γ-ray detection
  - Large density and high Z
  - Room temperature operation possible due large band gap
  - Cons
    - Mobilities are low
    - Charge collection, in particular of holes, is poor
    - Application is limited to thicknesses ≤10 mm
  - E = 2500 V/cm
  - Areas □30 x 30 mm^2

6.4. SCINTILLATION DETECTORS AND STORAGE PHOSPHORS

6.4.1. Basic principles

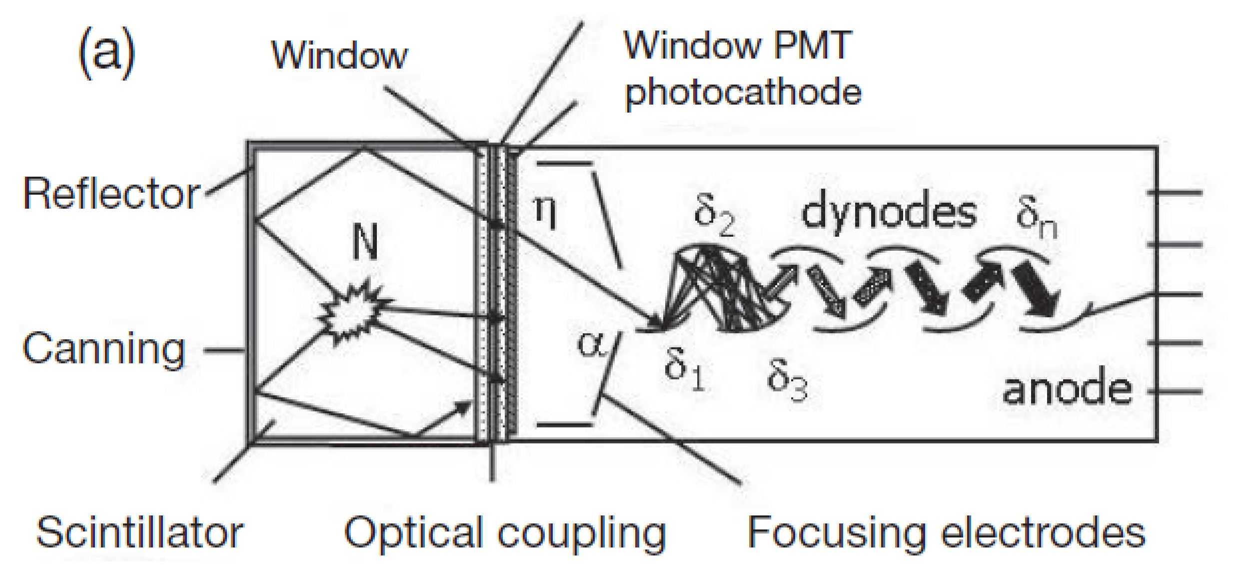
- Scintillation is prompt emission of light after radiation interaction
- In nuclear medicine, inorganic ionic crystals are most important
  - High density & Z
  - Fast response
  - High light yield
  - Large crystals can be grown
  - Primarily for X-ray and γ-ray detection
  - Metastable states (traps) are created in some materials
    - may live ms to months (storage phosphors)
- Organic scintillators are another group
  - Crystals, plastics and liquids
  - Low density & Z
  - Primarily for counting β particles

6.4. SCINTILLATION DETECTORS AND STORAGE PHOSPHORS

6.4.2. Light sensors

6.4.2.1. Photomultiplier tubes

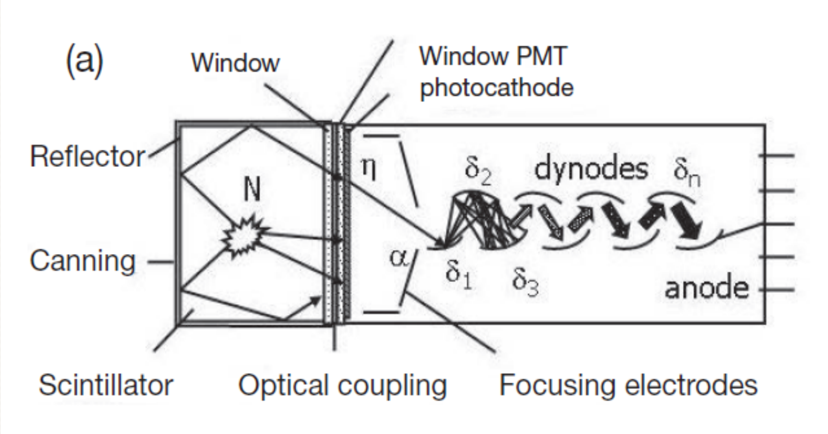
- ❑ A scintillation crystal is coupled to a PMT to make a detector
- ❑ Inside of entrance window to the evacuated glass envelope is covered with a photocathode which converts photons into electrons



6.4.2. Light sensors

6.4.2.1. Photomultiplier tubes

- Photocathode consists of thin layer of alkali materials with very low work functions
  - Examples
    - Bialkali K_2CsSb
    - Multialkali $Na_2KSb:Cs$
    - Negative electron affinity (NEA) material such as GaAs:Cs,O



- Conversion efficiency of PMT is called Quantum Efficiency η
  - Strongly wavelength dependent
    - At 400 nm, η = 25–40%

6.4. SCINTILLATION DETECTORS AND STORAGE PHOSPHORS

6.4.2. Light sensors

6.4.2.1. Photomultiplier tubes

- Emitted electrons focused onto first dynode via electrode structure
  - Applied voltage = 200–500 V
  - Collection efficiency $\alpha \approx 95\%$
  - Typical materials are BeO–Cu, Cs_3Sb and GaP:Cs
    - The latter is an NEA material
  - Electrons released by secondary emission if electron hits dynode
    - Focused onto next dynode
    - Secondary electrons emitted again
  - N = Number of dynodes = 8–12
  - Last dynode (anode) provides signal
  - Multiplication factor
    - $\delta \approx 5$ per dynode at inter-dynode voltage = 100 V
    - First dynode has higher multiplication factor $\delta_1 \geq 10$
      - Improves single-electron pulse resolution & signal to noise ratio

6.4.2. Light sensors

6.4.2.1. Photomultiplier tubes

- ☐ Signal properties
  - Starting with *N* photons in the scintillator
  - Assuming full light collection on the photocathode
  - N_{el} = Number of electrons at anode is given by:

$$N_{\mathrm{el}} = \delta_1 \delta^{n-1} \alpha \eta N$$

- ☐ Gains of 10^6–10^7 are obtained
- ☐ Negative high voltage (1000–2000 V) often used with anode at ground potential
- ☐ Operational care
  - Care must be taken of metal parts near the cathode
  - Detector housing should never be opened with voltage on
  - Exposure to daylight would damage the photocathode permanently

6.4. SCINTILLATION DETECTORS AND STORAGE PHOSPHORS

6.4.2. Light sensors

6.4.2.1. Photomultiplier tubes

- PMTs
  - Available with circular, square or hexagonal photocathodes
  - Cathode diameters = 10 - 150 mm
  - If diameter ~ 50 mm ⇨ length ~ 150 mm (including contact pins)
  - Also available pixelated with multi-anode

- Time resolution optimized by making special tubes with electron transit times as the anode, independent of cathode position where electron emitted

- Electron transit time ~ 30 ns
- Spread standard deviation ~ 250 ps
- Signal rise time ~ 1.5 ns

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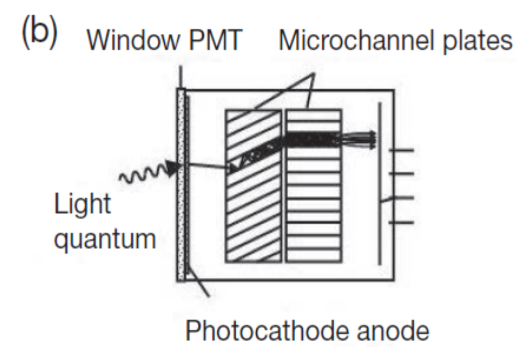
6.4.2. Light sensors

6.4.2.1. Photomultiplier tubes

☐ Microchannel plate (MCP) PMT

- Aimed at ultra-fast timing
- Replaces dynodes for electron multiplication
- Thickness ~ 1 mm
- Has large number of closely packed hollow glass tubes
- Channel diameter = 5–50 μm
- Inner tube surface is covered with a secondary emission material (e.g. PbO)
- The glass surfaces on the front and back side are covered with metal contacts
- Placed in vacuum
- 1000 V applied between contacts, positive on the back side



6.4.2.1. Photomultiplier tubes

- ❑ Microchannel plate (MCP)
  - An electron enters glass tube on front side & hits wall
  - Secondary electron emission occurs
    - Electrons pulled to back side by *E*
    - Hit channel wall & produce secondaries, etc.
    - Eventually leave tube at back
  - Electron multiplication ≤ 10^4

6.4.2.1. Photomultiplier tubes

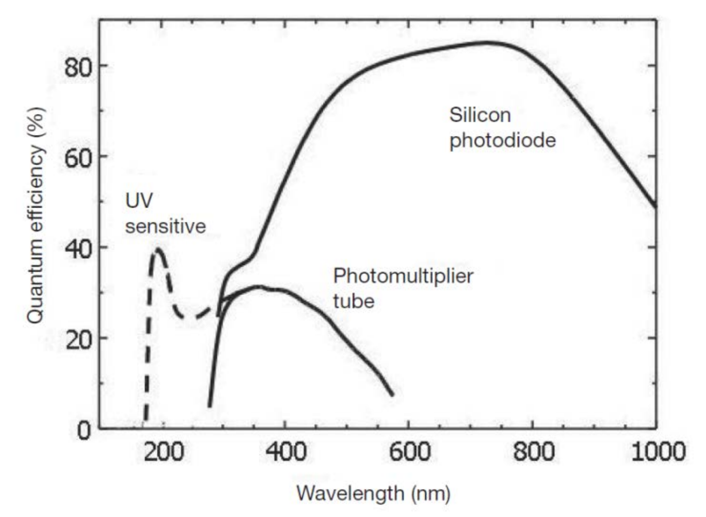
- ☐ MCP-PMT uses 2 MCPs at close distance
  - Structure called chevron
  - Glass tubes at an angle
    - Prevent ions from gaining too much energy
  - At 3000 V, stable gains ~ 10^6
  - Advantage: short path length of electrons
    - Transit times ~ few ns
    - Transit time spreads ~ 100 ps
  - Commercially available as:
    - Circular with diameter = 10 mm
    - Square with multi-anode structures
  - Sensitive between 115 nm (MgF_2 window) - infrared

6.4.2. Light sensors

6.4.2.2. Silicon based photon sensors

- Si photodiodes preferred in some applications
  - PMTs have large size, high voltages, small quantum efficiency and sensitivity to magnetic fields
  - Si diodes are usually p–i–n structure (PIN diodes)
  - Thickness = 2 mm including packaging
  - Shapes: circular, rectangular or square, up to 30 mm × 30 mm
  - Bias voltages < 150 V

- Si photodiodes preferred in some applications
  - Quantum efficiency can be > 80% at longer wavelengths



  - Disadvantages
    - Large capacitance = 20–300 pF
    - Large leakage current ~ 1–10 nA
    - Significant noise level
    - Affects energy resolution negatively

6.4. SCINTILLATION DETECTORS AND STORAGE PHOSPHORS

6.4.2. Light sensors

6.4.2.2. Silicon based photon sensors

☐ Avalanche photodiode (APD)

- Semiconductor analogue to proportional counter
- A high *E*-field is created in small zone
  - Drifting electron can gain enough energy to produce (e–h) pair
  - An avalanche results
  - Critical field for multiplication = 10^7 V/m
- Higher V → higher gain
- Voltages applied = 50–1500 V depending on type
  - Gains are M □1000
    - Lifts signal well above noise as compared to Si diode
  - At a certain gain, the advantage is optimal

6.4.2.2. Silicon based photon sensors

❑ Avalanche photodiode (APD)

- Break-down voltage V_{br}
  - Spontaneous charge multiplication occurs
- At voltages > V_{br}
  - For gains of M 10^5 –10^6
  - Geiger mode
  - Pulses are equal in magnitude
  - Signal quenching techniques have to be used
- Available as circular & square with areas = sub-mm^2 -1 cm^2
- Available with various pixelations
  - e.g. of 4 × 8 at 2.5 mm pitch & fill factor ≤ 40%

6.4. SCIENTILLATION DETECTORS AND STORAGE PHOSPHORS

6.4.2. Light sensors

6.4.2.2. Silicon based photon sensors

☐ Hybrid photomultiplier tube (HPMT)

- Voltage between photocathode & Si diode ~ 10 kV
- Si diode placed inside vacuum enclosure
- Photoelectrons accelerated in resulting *E* field
- Diode is relatively small
  - Reduces capacitance which reduces noise level
  - Need 3.6 eV to produce 1 e–h pair
  - 3000 e–h pairs produced per impinging electron
- Signals from one or more photons are well separated
- Possible overall gain with APD = 10^5
- Window diameters are as large as 70 mm

6.4. SCINTILLATION DETECTORS AND STORAGE PHOSPHORS

6.4.2. Light sensors

6.4.2.2. Silicon based photon sensors

☐ Silicon photomultiplier (SiPM)

- Array of tiny APDs operating in Geiger mode
- Dimensions: 20 × 20 μm^2 to 100 × 100 μm^2
- Number of APDs per mm^2 = 2500 – 100
- Fill factor from < 30% to 80% for smallest to largest dimensions
- All APDs signals are summed
- Time spread < 100 ps
- Excellent time resolutions

6.4.2.2. Silicon based photon sensors

- Silicon photomultiplier (SiPM)
  - Gains M = 10^5–10^6
    - Can easily obtain a signal from a single photon
    - Spontaneous Geiger pulses can be eliminated by setting a threshold above the one electron response
  - Available arrays
    - 2 × 2 pixels and 4 × 4 pixels
    - 3 × 3 mm^2 each
    - Pitch of 4 mm
    - A 16 × 16 pixel array of 50 × 50 mm^2 (recently introduced)
    - Blue sensitive SiPMs have detection efficiency of 25% at 400 nm, including a 60% fill factor

6.4. SCINTILLATION DETECTORS AND STORAGE PHOSPHORS

6.4.3. Scintillator materials

6.4.3.1. Inorganic scintillators

- ☐ Inorganic scintillator bandgap has to be relatively large so as to:
  - $E_{\mathrm{gap}} \geq 4$ eV
  - Avoid thermal excitation
  - Allow scintillation photons to travel in material without absorption
- ☐ Thus: inorganic scintillators are based on ionic-crystal materials

6.4. SCINTILLATION DETECTORS AND STORAGE PHOSPHORS

6.4.3. Scintillator materials

6.4.3.1. Inorganic scintillators

☐ Three steps scintillation photons production

1. Interaction with bulk material & thermalization of electrons and holes
    - Electrons go to bottom of conduction band
    - Holes go to top of the valence band
2. Transport of charge carriers to intrinsic or dopant luminescence centres
3. Interaction with these centres
    - Excitation
    - Relaxation
    - Scintillation

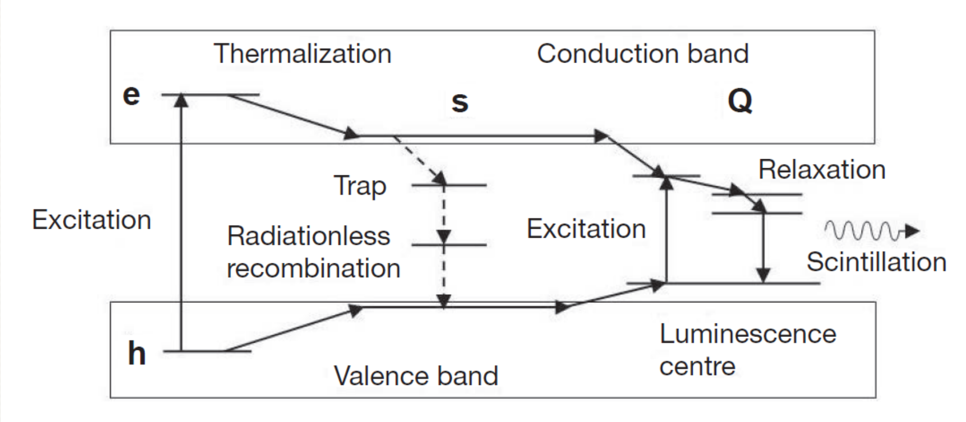
6.4.3. Scintillator materials

6.4.3.1. Inorganic scintillators

- Using this model, the number of photons N_{ph} produced under absorption of a gamma ray with energy E is:

$$N_{\mathrm{ph}} = \frac{E}{\beta E_{\mathrm{gap}}} SQ$$

  - $E/\beta E_{gap}$ = number of e–h pairs at bandgap edge
  - $\beta \approx 2.5$
  - *S* & *Q* are the efficiencies of steps 2. and 3. in previous slide



6.4. SCINTILLATION DETECTORS AND STORAGE PHOSPHORS

6.4.3. Scintillator materials

6.4.3.1. Inorganic scintillators

- Specifications of some inorganic scintillators

Scintillator	ρ (g/cm^3)	Z_{eff}	$1/\mu_{511}$ (mm)	Photoelectric effect (%)	λ_{max} (nm)	N_{ph} (photons/MeV)	R_{662} (%)	τ (ns)
NaI:Tl[a]	3.67	51	29	17	410	41 000	6.5	230
CsI:Tl	4.51	54	23	21	540	64 000	4.3	800, 10^4
BaF_2	4.88		23		220	1500		0.8
					310	10 000		600
$Bi_3Ge_4O_{12}$ (BGO)	7.1	75	10.4	40	480	8520		300
$LaCl_3$:Ce[a]	3.86	49.5	28	15	350	49 000	3.3	25
$LaBr_3$:Ce[a]	5.07	46.9	22	13	380	67 000	2.8	16
$YAlO_3$:Ce (YAP)	5.5	33.6	21	4.2	350	21 000	4.4	25
$Lu_{0.8}Y_{0.2}Al$:Ce (LuYAP)	8.3	65	11	30	365	11 000		18
Gd_2SiO_5:Ce (GSO)	6.7	59	14.1	25	440	12 500	9	60
Lu_2SiO_5:Ce,Ca (LSO)	7.4	66	11.4	32	420	~36 000	7	36–43
$Lu_{1.8}Y_{0.2}SiO_5$: Ce (LYSO)	7.1		12		420	30 000	7	40

[a] Hygroscopic

6.4. SCINTILLATION DETECTORS AND STORAGE PHOSPHORS

6.4.3. Scintillator materials

6.4.3.1. Inorganic scintillators

- The scintillators in the table are commercially available
- If hygroscopic, they are canned with reflective material
- Only BaF_2 and BGO have intrinsic luminescence centre
- Others have Tl^+ or Ce^{3+} ions as dopant luminescence centre
  - Ce doped scintillators show a relatively fast response
    - Of the order of tens of ns
    - Due to allowed 5d → 4f dipole transition of the Ce ion
  - Tl doped scintillators much slower because these transitions are forbidden

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6.4. SCINTILLATION DETECTORS AND STORAGE PHOSPHORS

6.4.3. Scintillator materials

6.4.3.1. Inorganic scintillators

❑ In general, mixed or co-doped crystals have advantages in:

- Crystal growing
- Response time
- Light yield
  - Large variation due to $S < 1$
- Afterglow effects

6.4. SCINTILLATION DETECTORS AND STORAGE PHOSPHORS

6.4.3. Scintillator materials

6.4.3.2. Organic scintillators — crystals, plastics and liquids

- Organic scintillators scintillation mechanism based on molecular transitions
    - Hardly affected by physical state of the material

- There are pure organic scintillator crystals such as
    - Anthracene
    - Plastics
    - Polystyrene
    - Liquids (Xylene)

6.4. SCINTILLATION DETECTORS AND STORAGE PHOSPHORS

6.4.3. Scintillator materials

6.4.3.2. Organic scintillators — crystals, plastics and liquids

- ☐ There are also solutions of organic scintillators in organic solid (plastic) and liquid solvents
  - Typical combinations: p-terphenyl in polysterene (plastic) and p-terphenyl in toluene
- ☐ There are also systems with POPOP added for wavelength shifting. In general:
  - Organic scintillators luminesce at ~420 nm, have a light yield of ~10 000 photons/MeV of absorbed γ-ray energy
  - Decay times are about 2 ns

6.4. SCINTILLATION DETECTORS AND STORAGE PHOSPHORS

6.4.3. Scintillator materials

6.4.3.3. Storage phosphors — thermoluminescence /optically stimulated luminescence

- ☐ Storage phosphor
  - Analogous to inorganic scintillator
  - Difference: a significant part of interaction energy is stored in long-living traps
    - These are the memory bits of a storage phosphor
  - The lifetime must be long enough for the application considered
- ☐ Readout is done by thermal (heating) or optical stimulation
  - Electron lifted from the trap into the conduction band and transported to a luminescence centre
  - The intensity of the luminescence is recorded
  - Processes called thermoluminescence & optically/photon stimulated luminescence

6.4. SCINTILLATION DETECTORS AND STORAGE PHOSPHORS

6.4.3. Scintillator materials

6.4.3.3. Storage phosphors — thermoluminescence /optically stimulated luminescence

- LiF:Mg,Ti is widely used
  - Commercial name TLD-100
  - Sensitivity = 50 μGy to 1 Gy
- LiF:Mg,Cu,P (GR-200)
  - Newer & more sensitive
  - Sensitivity = 0.2 μGy to 1 Gy
- Al_2O_3:C
  - Optically stimulated luminescent material
  - Recently introduced
  - Sensitivity = 0.3 μGy to 30 Gy
- Also used in radiography
- Used for dosimetry for > 50 years
  - Thermoluminescence dosimeter