Radiation Detectors

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How do we detect ionizing radiation?

Indirectly, by its effects as it traverses matter?

What are these effects?

- Ionization and excitation of the atoms and molecules
- Heat

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Types of Ionizing Radiation Detectors

- Film
- Gas or liquid filled ionization detectors
- Scintillation crystal detectors
- Semiconductor crystal detectors

} These 3 produce electronic signals

"Counters" measure the number of particles that interact
"Spectrometers" can count but also can measure the distribution of deposited energy (the amplitude of each pulse is proportional to the amount of ionization charge deposited which is proportional to the energy deposited in the detector by the interaction)
"Dosimeters" measure the sum energy deposited for multiple events

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Pulse and Current Modes of Operation

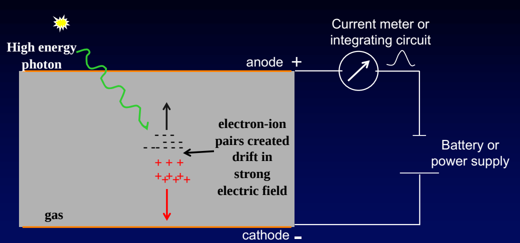
Pulse Mode (Nuc Med imaging systems and well-counters–these are spectrometers): Electronic signal from each event is processed individually

- Advantage: Energy information from each event and rate (energy of event is proportional to the amount of charge deposited)
- Disadvantage: Pulse pile-up and system dead-time

Current Mode (Nuc Med dose calibrators and most all other Radiology imaging systems): Signals are summed together over a time period forming a net signal.

- Advantage: Can perform at higher incoming radiation intensity and measure dose rate deposited in detector
- Disadvantage: Lose all interaction rate or energy information of incoming radiation

Gas Filled Detectors



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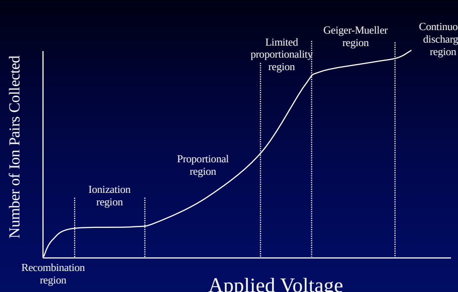
Gas Filled Detectors



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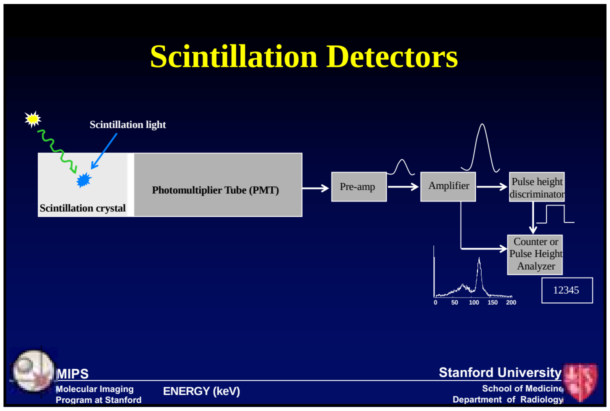
Scintillation Detectors
Scintillation light
Scintillation crystal
Photomultiplier Tube (PMT)
Pre-amp
Amplifier
Pulse height discriminator
Counter or Pulse Height Analyzer
12345
0 50 100 150 200
ENERGY (keV)
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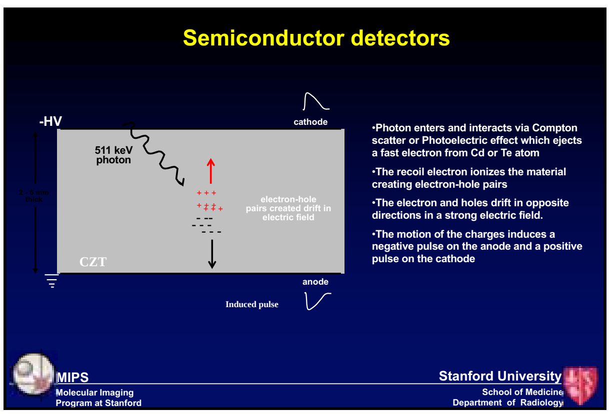
Semiconductor detectors
-HV
cathode
511 keV photon
electron-hole pairs created drift in electric field
CZT
anode
Induced pulse
•Photon enters and interacts via Compton scatter or Photoelectric effect which ejects a fast electron from Cd or Te atom
•The recoil electron ionizes the material creating electron-hole pairs
•The electron and holes drift in opposite directions in a strong electric field.
•The motion of the charges induces a negative pulse on the anode and a positive pulse on the cathode
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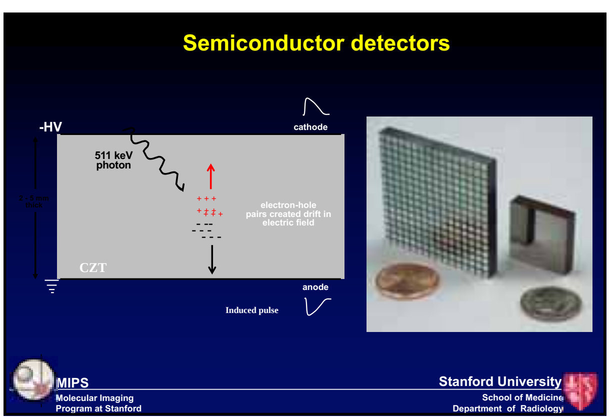
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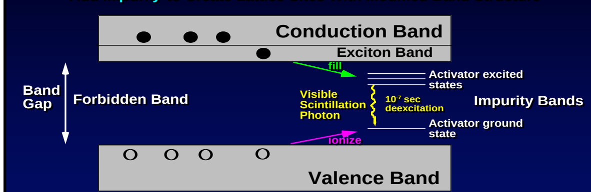
Inorganic Scintillation Crystals

Material	Density (g/cm^3)	Effective Z	Peak Wavelength λ_{max}(nm)	Refractive Index at λ_{max}	Decay Time (ns)	Light Yield (Photons/MeV)
NaI(Tl)	3.67	51	410	1.85	230	38,000
$Bi_4(GeO_4)_3$	7.13	75	480	2.15	300	8,200
CsI(Tl)	4.51	54	540	1.80	1000	39,000
$Lu_2(SiO_4)O$:Ce	7.40	66	420	1.82	40	28,500
$Gd_2(SiO_4)O$:Ce	6.71	59	440	1.85	60	9,500
BaF_2	4.88	65	220	1.56	0.6	10,000
CaF_2(Eu)	3.19	17	435	1.44	900	17,000

Inorganic Scintillation Crystal Mechanism

Characteristic Electronic Band Structure of Crystals

Add Impurity to Create Lattice Sites With Modified Band Structure



High Z, High Density

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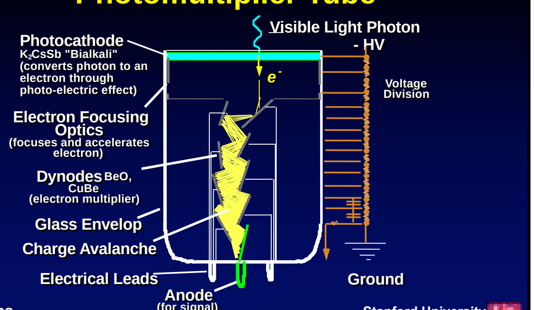
Photomultiplier Tube



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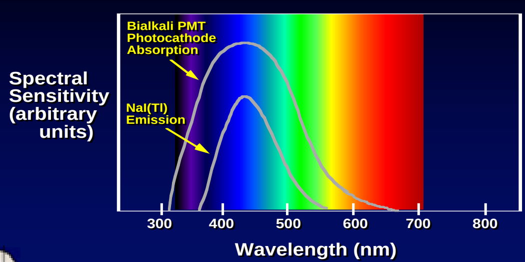
Scintillator-PMT Photocathode Spectral Match



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Important Performance Parameters of Radiation Detectors

- Energy Resolution
- Timing resolution
- Efficiency
- Count rate performance

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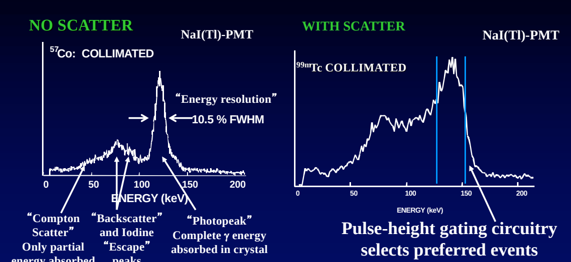
Spectrometers can measure pulse height "spectrum" (a.k.a. "energy spectrum")



Pulse-height gating circuitry selects preferred events (not too narrow a window)

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Detection Efficiency (a.k.a. "sensitivity")

Probability that emitted radiation will be detected:

Efficiency = (number detected) / (number emitted)
= (geometric efficiency) x (intrinsic efficiency)
= (number reaching detector)/(number emitted) x (number detected)/(number reaching detector)

Intrinsic efficiency= $1-e^{-\mu x}$

Non-imaging detectors used in clinic

- **Thyroid Probe ("Collimated" scintillation detector)**
- **Well Counter ("Well-shaped" scintillation detector)**
- **Dose Calibrator ("Well-shaped" gas detector)**
- **Geiger Counter ("panel shaped" gas detector)**

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Radiopharmaceutical Properties

- Labels functional properties rather than anatomy
- Uses short-lived nuclear emissions (γ and β) with appropriate energy for low dose
- Non-toxic and uncontaminated
- Localize in the tissue or organ of interest and not elsewhere
- Easy to make, low cost, non toxic

Example localization (uptake) mechanisms:
1. Active transport for uptake by tissue or organ (e.g. thyroid)
2. Compartmental localization (e.g. blood pool)
3. Exchange or diffusion (e.g. bone)
4. Perfusion (e.g. liver)
4. Phagocytosis (e.g. liver)
5. Capillary blockade (e.g. lung)
6. Cell sequestration (e.g. spleen)

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Example: Chemistry of Positron Emitters

Commonly used positron emitting tracers in medicine

Radiotracer	Biological Analog	Measured Response
2-deoxy-2-(^{18}F)fluoro-D-glucose (FDG)	Glucose	Glucose metabolism, Hexokinase activity
(^{11}C)-Acetate	Acetate	Fatty acid metabolism
(^{13}N)-Ammonia	Ammonia	Tissue perfusion
(^{15}O)-Water	Water	Tissue perfusion, Blood flow
5-(^{18}F)-fluoro-DOPA	Dopamine	Amino acid metabolism
(^{18}F)-fluoroacyclovir	Acyclovir	Thymidinekinase activity
(^{18}F)-fluoromethyltyrosine	Tyrosine	Amino acid metabolism

The radiochemicals are synthesized from the radioactive targets

Half-lives: ^{11}C 20 min. ^{13}N 10 min. ^{15}O 2 min. ^{18}F 1.8 hr.

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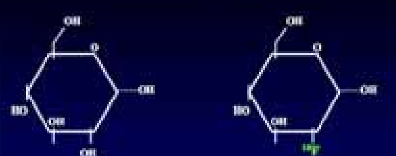
Chemistry of Positron Emitters

^{18}F-Fluorodeoxyglucose (FDG)



D-Glucose — 2-Deoxy-2-Fluoro-D-Glucose

- Glucose and FDG compete for transport into cells and phosphorylation by hexokinase.
- FDG-6-phosphate is not metabolized via the glycolytic pathway and is essentially trapped in the cell.

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