Bioengineering 508:
Physical Aspects of Medical Imaging
http://courses.washington.edu/bioen508/

For questions, remarks, discussions, errors in the book:
Class Discussion Board (link from class website)
Monitored by instructors frequently

Organizer: Paul Kinahan, PhD
Adam Alessio, PhD
Ruth Schmitz, PhD
Lawrence MacDonald, PhD

Imaging Research Laboratory
http://depts.washington.edu/nucmed/IRL/
Department of Radiology
University of Washington

Homework
for Oct. 25

1. Read Suetens sections 8.5 – 8.10

2. Find 2 medical images of abnormal physiology using SPECT or PET

Place these images in a document
- Write 1–2 brief sentences describing each image
- Write 1–2 brief sentences describing differences between the images.
- Write 1–2 brief sentences describing what the image values represent physically.

Announcements

1. Today's homework can be handed in tomorrow for those having trouble finding planar gamma camera images.

2. Signup sheet indicating names of groups for class project

   (Prof. Kinahan will assign undesignated students tomorrow)

3. Field trip to UW Radiology Dept. will be Sat. 10/28

   late morning or early afternoon preference?

4. NO CLASS on Nov. 1!

   The exam will be administered over the web – take-home exam.

Radiation Physics
Nuclear Medicine
Detectors and Systems

18 Oct. 2006
Larry MacDonald
macdon@u.washington.edu
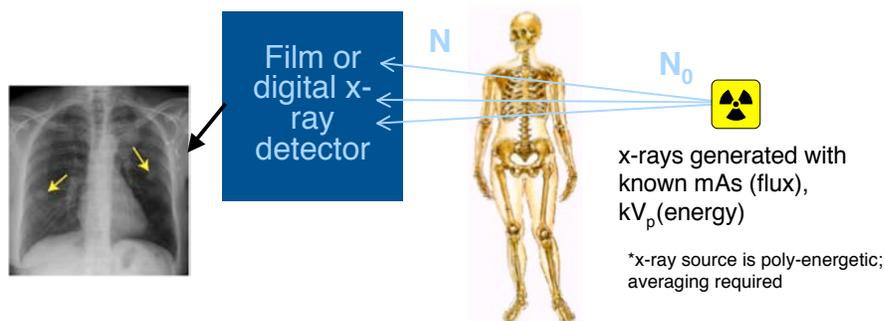
Overview of today's lecture

- **Emission vs. Transmission Imaging**

- Nature of nuclear radiation

    - Isotopes used in nuclear medicine

- Detection methods

- Counting statistics

- Imaging systems

    - Planar gamma scintigraphy

Tomographic systems (SPECT & PET)
covered in a later lecture

Emission vs. Transmission imaging

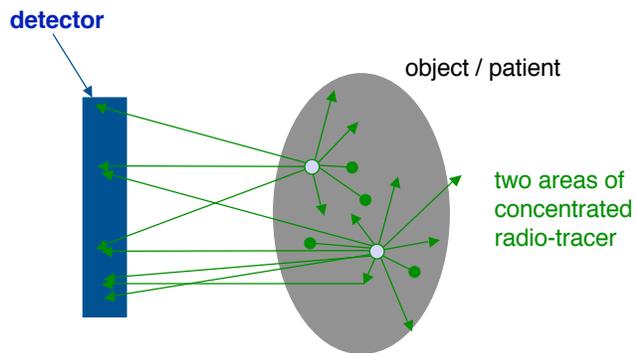**Transmission imaging; X-ray methods** (radiograph, CT, mammography, angiography)
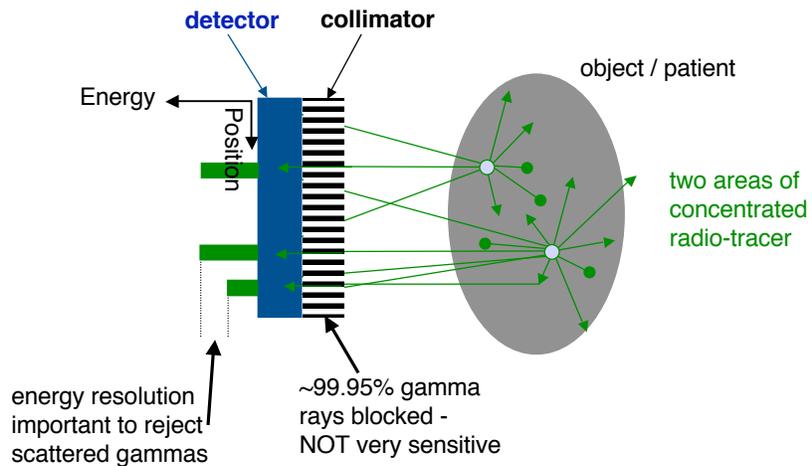**Radiation position & strength (number, energy*) is *known***

N

N_0

Film or digital x-ray detector

x-rays generated with known mAs (flux), kV_p(energy)

*x-ray source is poly-energetic; averaging required

$N = N_0 e^{-\mu x}$ —> N_0 known, measure N, infer μ
what ambiguity exists?

Emission imaging
**Radiation position & strength *unknown*
Energy *is* known (mono-energetic)**

detector

object / patient

two areas of
concentrated
radio-tracer

Scintillation Camera

detector   collimator

object / patient

Energy

Position

two areas of
concentrated
radio-tracer

energy resolution
important to reject
scattered gammas

~99.95% gamma
rays blocked -
NOT very sensitive

Emission vs. Transmission imaging

Transmission imaging (x-ray methods)
   Measures attenuation coefficient:
   μ ~ density of tissue —-> ANATOMY

Emission imaging (gamma-ray methods; planar, SPECT, PET)
   Measures concentration of injected radio-
   pharmaceutical —-> corresponds to WHAT?

100s of radio-pharmaceuticals designed to highlight a variety of PHYSIOLOGICAL processes.
Referred to as
   "functional imaging"
   "molecular imaging"

Overview of today's lecture

- Emission vs. Transmission Imaging

- **Nature of nuclear radiation**

   - Isotopes used in nuclear medicine

- Detection methods

- Counting statistics

- Imaging systems

   - Planar gamma scintigraphy

Nuclear radiation results from unstable nuclei

Nuclear stability is a balance between electromagnetic repulsion of protons and strong force interaction among all nucleons (protons and neutrons).

There are ~ 2,450 isotopes of the ~ 100 elements in the Periodic Table, ~300 of which are naturally occurring, the others are human-made.

Several mechanisms for unstable nuclei to decay to stable isotopes: fission, α-, β-, γ-emission, e^- capture.

Frequently there are multiple decay steps to reach stability.

Each decay step is described by an exponential process with a characteristic decay time —-> Half-life of the isotope $T_{1/2} = \tau / \ln(2)$

$$N = N_0 e^{-t/\tau}$$

Types of radiation relevant to Nuclear Medicine

Particle	Symbol	Mass (MeV/c^2)	Charge (e$^-$)
Electron	e-, β -	0.511	-1
Positron	e+, β+	0.511	+1
Alpha	α	3700	+2
Photon	γ	no rest mass	none

Electron mass   = 9.11×10^{-31} kg
Electron charge = 1.6×10^{-19} Coulombs
Joules-to-electronVolts: 1.6×10^{-19} J/eV
$E = mc^2$

α Particle Range in Matter
2 protons + 2 neutrons (helium nucleus)
mono-energetic
NOT USED FOR IMAGING

- Loses energy in a more or less continuous slowing down process as it travels through matter.

- The distance it travels (range) depend only upon its initial energy and its average energy loss rate in the medium.

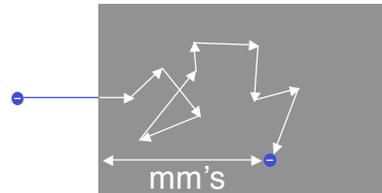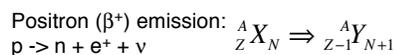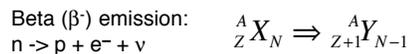- The range for an α particle emitted in tissue is on the order of μm's.

+ + + + + + + + + + + + + + + +

μm's
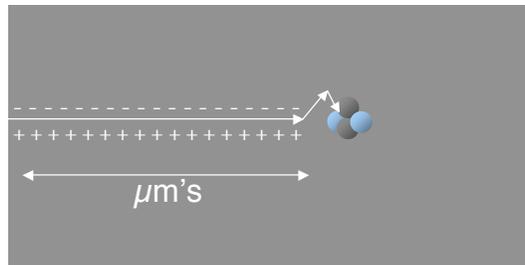
β Decay
continuous energy spectrum
Autoradiography (*in-vitro* imaging)
Proximity imaging (? research probes)

- β particle ranges vary from one electron to the next, even for βs of the same energy in the same material.

- This is due to different types of scattering events the β encounters (i.e., scattering events, bremsstrahlung-producing collisions, etc.).

- The β **range** is often given as the **maximum distance** the **most energetic** β can travel in the medium.

- The range for β particles emitted in tissue is on the order of mm's.

Beta (β⁻) emission:
n -> p + e⁻ + ν

$$_Z^A X_N \Rightarrow \, _{Z+1}^A Y_{N-1}$$

Positron (β⁺) emission:
p -> n + e⁺ + ν

$$_Z^A X_N \Rightarrow \, _{Z-1}^A Y_{N+1}$$

mm's

Interactions of Photons with Matter

Exponential Penetration: $N = N_0 e^{-\mu x}$

μ_{PE}, μ_{CS}, etc., dependent on E, Z, density.
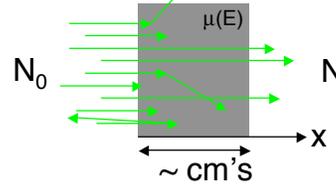
<u>Photoelectric effect (μ_{PE})</u>
all photon energy transferred to an e⁻
photon is absorbed; ceases to exist

<u>Compton scattering (μ_{CS})</u>
photon 'bounces' off an e⁻
part of the photon energy transferred to the e⁻,
lower energy photon redirected between $0^\circ - 180^\circ$

Pair production
positron-electron pair is created
requires photons above 1.022 MeV

Coherent (Rayleigh) scattering
photon deflected with very little energy loss
only significant at low photon energies (<50 keV)

Nuclear Medicine Radionuclide Requirements

Emission imaging
Charged, massive particles (α-, β-rays) cannot penetrate tissue for emission imaging.
—-> need Gamma-Ray emitters [exception: β^+ emitters for PET]

Half-life
"Too long" leaves damaging radiation in patient after imaging is complete, delivering unnecessary dose.
"Too short" does not permit production, preparation, delivery, administration, and internal distribution for practical imaging tasks.
—-> Typically many minutes – hours – a few days is considered about right.

Energy of Gamma-Ray
If the energy is "too low" a majority of the photons will be attenuated and not reach the camera (cf. α-, β-rays) .
If the energy is "too high" then the γ-rays will pass through the camera without being absorbed by the detector and it is difficult to collimate.
—-> Energies of ~100–500 keV are used.

Complexity
A decay scheme with "too many" emissions confounds the imaging process.
—-> Select isotopes with relatively simple decays schemes; ideally one or two γ-rays, no β- or α-rays.

Chemical properties
Isotope must be incorporated into a pharmaceutical or other organic compound.
—-> Isotopes amenable to chemical, pharmaceutical, and sterile processing.

List of Nuclear Medicine Radionuclides
for "single photon" imaging (i.e. excluding PET)

Isotope	Gamma energy(keV)	Half-life
• **Tc99m**	**140.5**	**6.03 hours**
• I-131	364, 637	8.06 days
• I-123	159	13.0 hours
• I-125	35	60.2 days
• In-111	172, 247	2.81 days
• Tl-201	~70, 167	3.044 days
• Ga-67	93, 185, 300	3.25 days

http://en.wikipedia.org/wiki/Radiopharmaceutical

Technetium-99m

^{99m}Tc is a gamma emitter: 140 keV

| Name	Investigation	Route of administration	In-vitro / in-vivo	Imaging / non-imaging
Tc99m-pertechnetate	Thyroid uptake and thyroid imaging			
	Stomach and salivary gland imaging			
	Meckel's diverticulum imaging			
	Brain imaging	IV	In-vivo	Imaging
	Micturating cystogram			
	First pass blood flow imaging			
	First pass peripheral vascular imaging			
Tc99m-pertechnetate	Lacrimal imaging	Eye drops	In-vivo	Imaging
Tc99m-Human albumin	Cardiac blood pool imaging	IV	In-vivo	Imaging
Tc99m-Human albumin	Peripheral vascular imaging	IV	In-vivo	Imaging
Tc99m-Human albumin macroaggregates or microspheres	Lung perfusion imaging	IV	In-vivo	Imaging
Tc99m-Human albumin macroaggregates or microspheres	Lung perfusion imaging with venography	IV	In-vivo	Imaging
Tc99m-Phosphonates and phosphates	Bone imaging	IV	In-vivo	Imaging
Tc99m-Phosphonates and phosphates	Myocardial imaging	IV	In-vivo	Imaging
Tc99m-DTPA (diethylenetriaminepenta-acetic acid)	Renal imaging			
	First pass blood flow studies			
	Brain imaging	IV	In-vivo	Imaging
Tc99m-DTPA (diethylenetriaminepenta-acetic acid)	Lung ventilation imaging	Aerosol inhalation	In-vivo	Imaging
Tc99m-DMSA(V) (dimercaptosuccinic acid)	Tumour imaging	IV	In-vivo	Imaging
Tc99m-DMSA(III) (dimercaptosuccinic acid)	Renal imaging	IV	In-vivo	Imaging
Tc99m-Colloid	Bone marrow imaging			
	GI Bleeding	IV	In-vivo	Imaging
Tc99m-Colloid	Lymph node imaging	Interstitial	In-vivo	Imaging
Tc99m-Colloid	Oesophageal transit and reflux imaging	Oral	In-vivo	Imaging
Tc99m-Colloid	Lacrimal imaging	Eye drops	In-vivo	Imaging
Tc99m-HIDA (Hepatic iminodiacetic acid)	Functional biliary system imaging	IV	In-vivo	Imaging
Tc99m-Denatured red bood cells	Red cell volume	IV	In-vitro	Non-imaging
Tc99m-Red blood cells	GI bleeding			
	Cardiac blood pool imaging			
	Peripheral vascular imaging	IV	In-vivo	Imaging
Tc99m-MAG3 (mercaptoacetyltriglycine)	Renal imaging			
	First pass blood flow imaging	IV	In-vivo	Imaging
Tc99m-HMPAO (Hexamethyl-propylene amine oxime)	Cerebral blood flow imaging	IV	In-vivo	Imaging
Tc99m-HMPAO (Hexamethyl-propylene amine oxime) labelled leucocytes	Infection/inflammation imaging	IV	In-vivo	Imaging
Tc99m-Sestamibi	Parathyroid imaging			
	Non-specific tumour imaging	IV	In-vivo	Imaging
	Thyroid tumour imaging			
	Breast imaging			
	Myocardial imaging			
Tc99m-Sulesomab (IMMU-MN3 murine Fab'-SH antigranulocyte monoclonal antibody fragments)	Infection/inflammation imaging	IV	In-vivo	Imaging
Tc99m-Technegas	Lung ventilation imaging	Inhalation	In-vivo	Imaging
Tc99m-Human immunoglobulin	Infection/inflammation imaging	IV	In-vivo	Imaging
Tc99m-Tetrofosmin	Parathyroid imaging			
	Myocardial imaging	IV	In-vivo	Imaging
Tc99m-ECD (ethyl cysteinate dimer)	Brain imaging	IV	In-vivo	Imaging

Single photon isotope production

Nuclear Reactor

Neutron bombardment of target isotopes leads to fission with useful radio-isotope fragments.

Generator

Long-lived parent isotope decays to short-lived daughter radio-isotope for use in the clinic (parent produced in, e.g., a nuclear reactor).

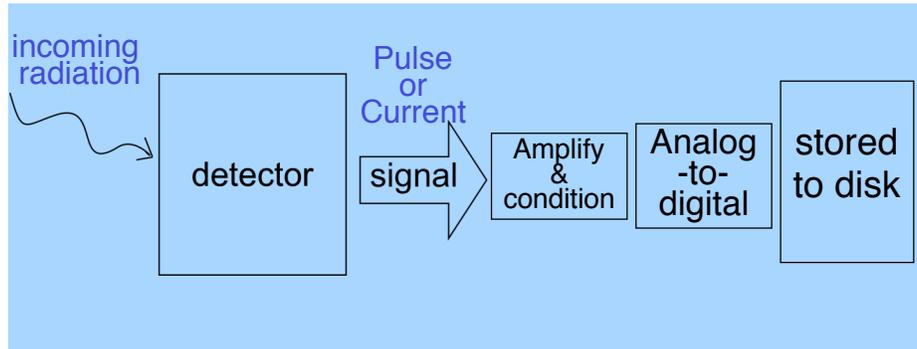Daughter separated from parent chemically in the 'generator'.
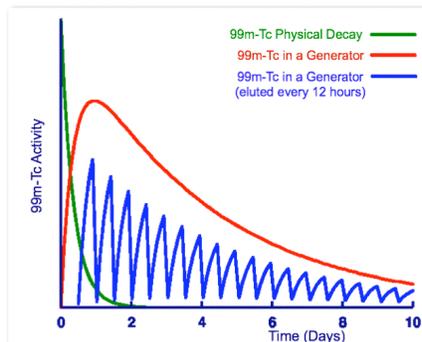
Cyclotron

Accelerates charged particles (e⁻, p, α, ^{2}H) that collide with targets resulting in radio-isotopes. Used to generate PET radio-isotopes.

Overview of today's lecture

- Emission vs. Transmission Imaging

- Nature of nuclear radiation

  - Isotopes used in nuclear medicine

- **Detection methods**

- Counting statistics

- Imaging systems

  - Planar gamma scintigraphy

Basic Radiation Detector System

incoming radiation → detector → **Pulse or Current** signal → Amplify & condition → Analog-to-digital → stored to disk

Basic Radiation Detector Systems

<u>What do you want to know about the radiation?</u>

Energy?

Position (where did it come from)?

How many / how much?

<u>Important properties of radiation detectors</u>

(depends on application)

Energy resolution

Spatial resolution

Sensitivity

Counting Speed

Pulse Mode versus Current Mode

- Pulse mode
  - Detect individual photons
  - Required for NM imaging applications
- Current mode
  - Measures average rates of photon flux
  - Avoids dead-time losses
  - Typically used in x-ray systems (CT)

Types of Radiation Detectors

detection modes / functionality

- Counters
  - Number of interactions
  - Pulse mode
- Spectrometers
  - Number and energy of interactions
  - Pulse mode
- Dosimeters
  - Net amount of energy deposited
  - Current mode
- Imaging Systems
  - CT = current mode
  - NM = pulse mode

Types of Radiation Detectors

physical composition

- Gas-filled detectors

- Solid-state (semiconductor) detectors

- Organic scintillators (liquid & plastic)

- Inorganic scintillators

scintillators operate with a
photo-sensor
(i.e. another detector)

Radiation detectors used in Nuclear Medicine
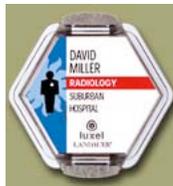
Gas-filled Detectors
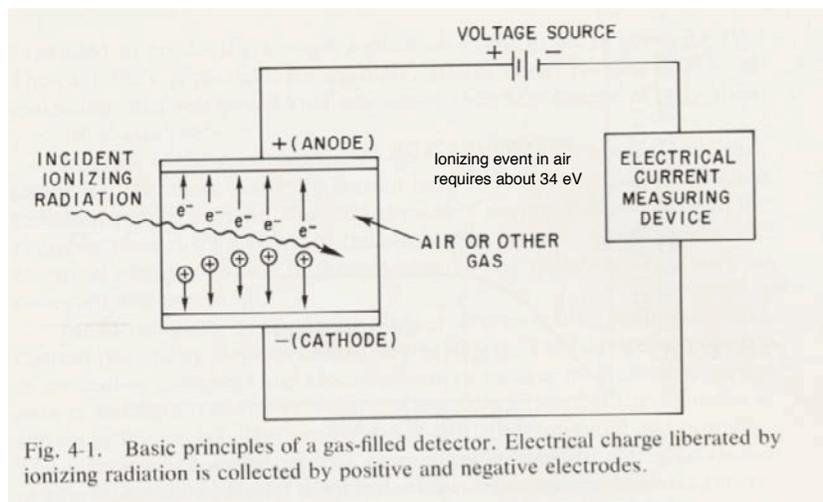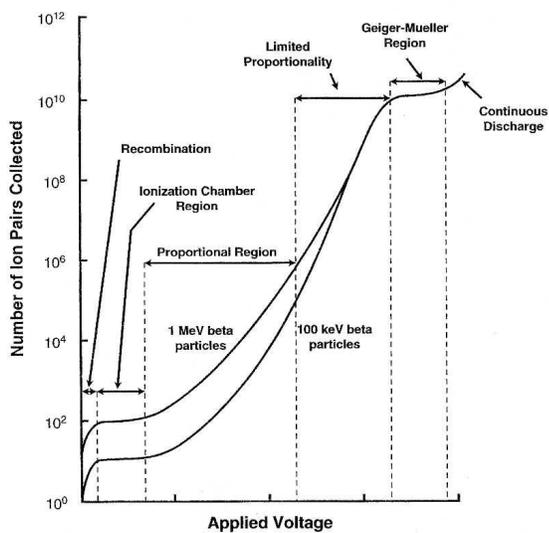## Can be used for imaging, but low sensitivity (low density)

Fig. 4-1. Basic principles of a gas-filled detector. Electrical charge liberated by ionizing radiation is collected by positive and negative electrodes.

Gas-filled detectors
(operates in three ranges)

Geiger-Muller counters

Proportional counters

Ionization chambers
– Radiation survey meters
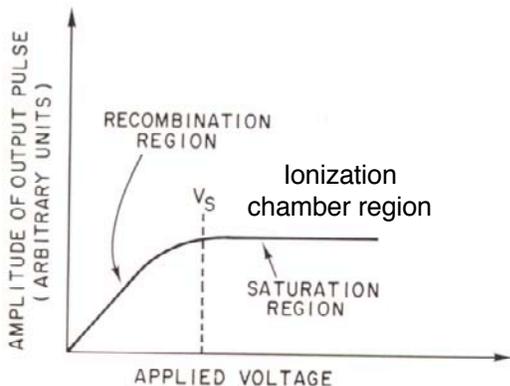– Dosimeters (dose calibrator)

Ionization Chambers

Fig. 4-2. Voltage response curve (charge collected versus voltage applied to the electrodes) for a typical ionization chamber. In usual operation, applied voltage exceeds saturation voltage V_s to ensure complete collection of liberated charge.

ATOMLAB 200
Dose Calibrator

No amplification
No dead-time
Signal = liberated charge
Settings for different isotopes
Calibrations

Geiger-Muller counters
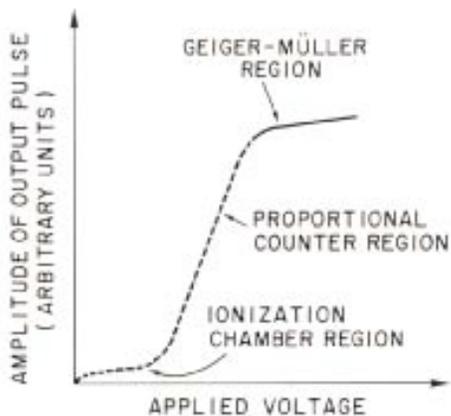
Fig. 4-10. Voltage response curve (pulse amplitude versus applied voltage) for a GM counter.

No energy info
Long dead-time
Thin window probe

Organic Liquid Scintillators
(NOT USED FOR IMAGING)

- Organic solvent – must dissolve scintillator material and radioactive sample
- Primary scintillator (p-terphenyl and PPO)
- Secondary solute (wave-shifter)
- Additives (e.g., solubilizers)
- **Effective for measuring <u>beta particles</u>** (e.g., H-3, C-14).
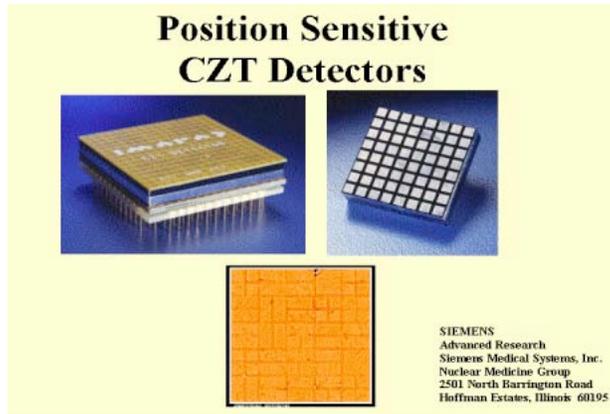

Liquid scintillator
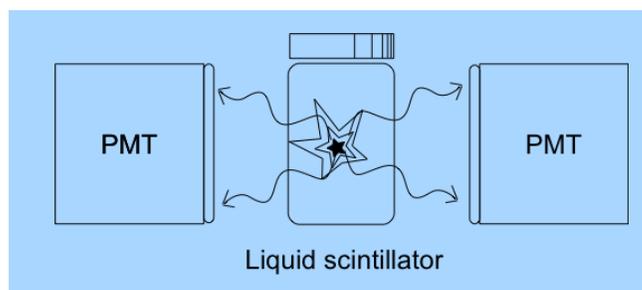
Semiconductor Detectors

- Works on same principle as gas-filled detectors (i.e., production of electron-hole pairs in semiconductor material)

- Only ~3 eV required for ionization (~34 eV, air)

- Usually needs to be cooled (thermal noise)

- Usually requires very high purity materials or introduction of "compensating" impurities that donate electrons to fill electron traps caused by other impurities

Semiconductor Detectors

- High purity germanium – need liquid nitrogen (77K)
- $Cd_{(1-x)}Zn_xTe$ detectors – can operate at room temperature

Inorganic Scintillators
(physical characteristics)

Absorption of radiation lifts electrons from valence to conduction band

Impurities (activators) create energy levels within the band gap permitting visible light scintillations

Inorganic Scintillators
(physical characteristics)

relevant <u>detector property</u>
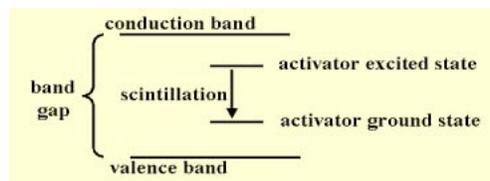
	Nal(Tl)	BGO	LSO(Ce)	GSO(Ce)	
Density (gm/cm^3)	3.67	7.13	7.4	6.71	
Effective Atomic Number	51	75	66	59	sensitivity
Attenuation Coefficient (@ 511 keV, cm^{-1})	0.34	0.955	0.833	0.674	
Light Output (photons/Mev)	40K	~8K	~30K	~20K	energy & spatial resol.
Decay Time	230 ns	300 ns	12 ns 40 ns	60 ns	counting speed
Wavelength	410 nm	480 nm	420 nm	430 nm	
Index of Refraction	1.85	2.15	1.82	1.85	photo-sensor matching
Hygroscopy	yes	no	no	no	manufacturing / cost
Rugged	no	yes	yes	no	
use	SPECT	PET	PET	PET	

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photo-sensor needed with scintillators
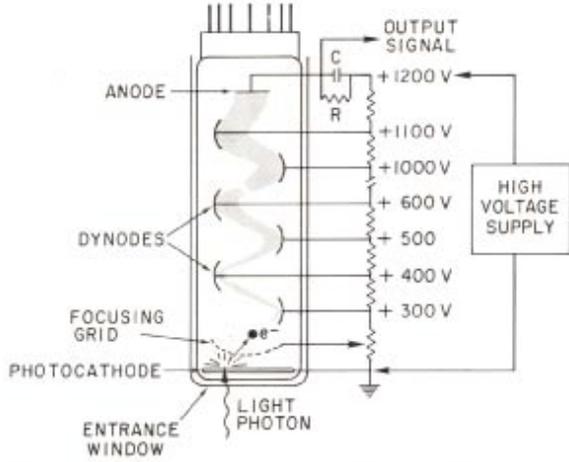
Photomultiplier Tube (PMT)

Fig. 4-14. Basic principles of a photomultiplier (PM) tube. (Note: Three dynode stages omitted.)