

Instrumentation for Detection of Ionizing Radiation: Principles and Practice

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1. Ionizing Radiation

a) Direct –

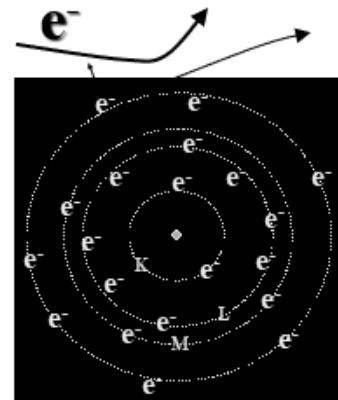
- i. Energetic electrically charged particles that ionize atoms and molecules in an absorbing medium
- ii. Have sufficient kinetic energy to free bound electrons as they pass through the medium.
- iii. Interact through electrostatic/Coulombic force.
- iv. Examples: electrons, protons, alpha particles, nuclear fragments, charged molecules

b) Indirect –

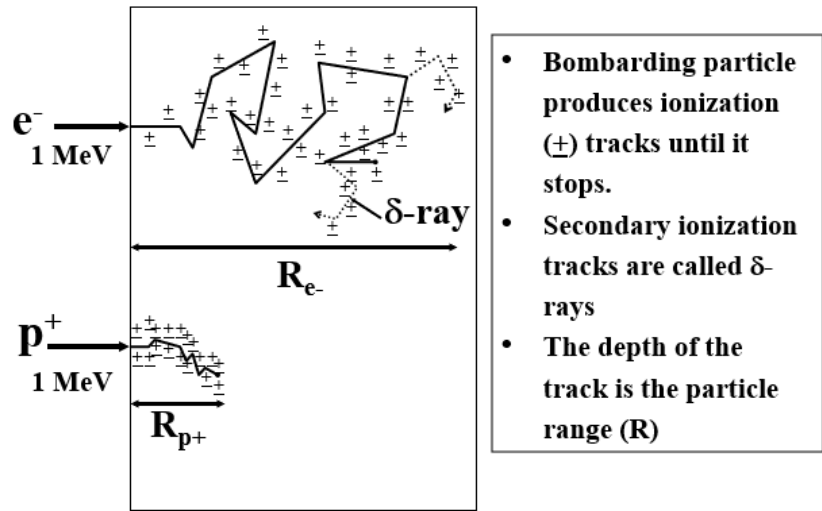
- i. Energetic uncharged particles that ionize atoms and molecules in an absorbing medium:
- ii. Collide with and deliver energy to charged particles in the absorbing medium, which in turn produce ionization.
- iii. Examples: gamma rays, x-rays, & neutrons.

2. Coulombic Collisions

- a) Collision between charged particles involve the Coulombic force of attraction and repulsion, rather than actual contact.
- b) Energy is transferred to the orbital electron. Low energy transfer below binding energy heats object. High energy transfer greater than binding energy ejects the electron, leaving behind an ionized atom.
- c) Energy transferred to the electrons is locally absorbed.



3. Charged Particle Tracks



4. Particle Range: The range (depth) of particle penetration depends on:

- Particle kinetic energy - The higher its kinetic energy, the greater its range.
- Particle mass - Lighter particles of the same kinetic energy have greater range, due to its higher velocity ($v=1/2mv^2$)
- Particle charge - Particles with less charge have greater range. Its range is inversely proportional to the square of its charge.
- Absorbing medium density - The range is inversely proportional to density. The higher the density of the medium the shorter the range.

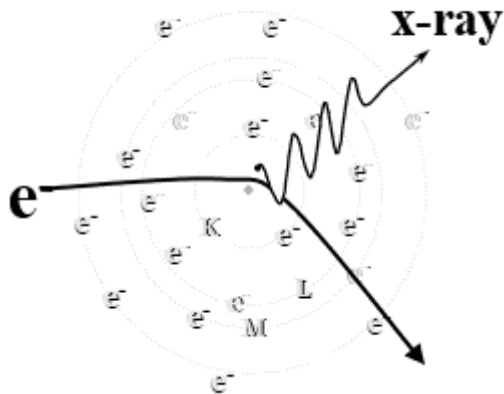
5. Range of Charged Particles

Range R (mm)

Energy (keV)	Air		Soft Tissue	
	e^- or e^+	α	e^- or e^+	α
10	1.6	0.10	0.002	<.0001
100	160	1.0	0.2	0.0014
1,000	3,300	5.0	4.0	0.0072
10,000	41,000	105	50	0.1400

6. Radiative Collision

- a) Collision occurs between charged particle in the vicinity of the nucleus. The particle brakes (slows down) releasing the energy loss as an x-ray. Also known as **bremsstrahlung** radiation.
- b) ~1% of kinetic energy transfer to x-ray; depends on atomic number.
- c) Energy transferred to x-ray not absorbed locally.



7. Interactions of Photons with Matter

- a) Thompson/Raleigh/Coherent Scattering
- b) Photoelectric effect
- c) Compton scattering
- d) Pair production
- e) Photo-nuclear disintegration

Photon Interaction vs. Energy

Method of Interaction	Energy of Prevalence
Coherent scattering	< 10 keV
Photoelectric effect	10 - 200 keV
Compton effect	100-3000 keV
Pair production	> 1022 keV
Photonuclear disintegration	> 10 meV

Energy & Atomic Number Dependence

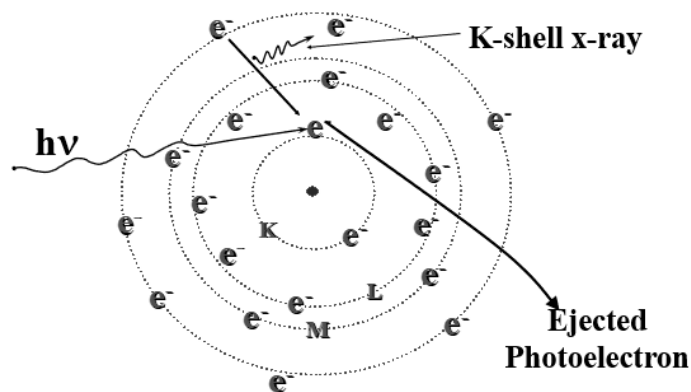
Method of Interaction	Photon Energy	Absorber Atomic #	Absorber Density
Photoelectric	$1/E^3$	Z^3	ρ
Compton	$\sim 1/E^{0.1}$	$N_0 Z^*$	ρ
Pair Production	$\log(E);$ $h\nu > 1022 \text{ keV}$	Z	ρ

8. Thompson/Raleigh/Coherent Scattering

- Target is with whole atom; No energy transfer: $h\nu' = h\nu$
- Prevalent only at low energies $< 10 \text{ keV}$

9. Photoelectric effect

- K-shell is primary target
- Total transfer of photon energy to orbital electron
- Kinetic energy of photoelectron = $KE_{PE} = h\nu - \text{Binding Energy}$
- Secondary emission of K-shell x-ray or Auger electron

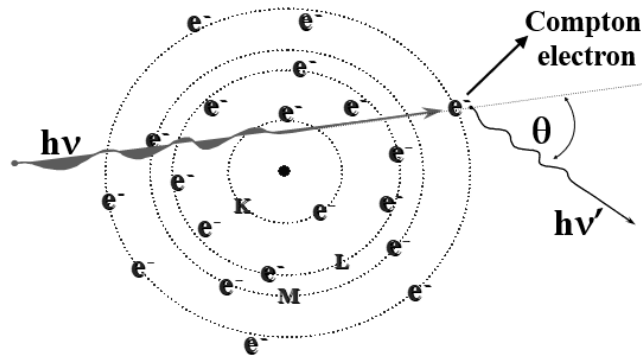


10. Compton scattering

- a) Outer-shell electrons are primary target
- b) Energy transfer shared between Compton electron and scattered photon

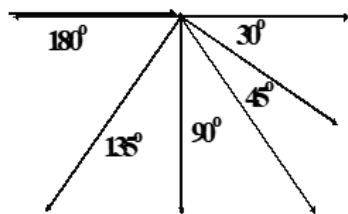
$$h\nu = h\nu' + KE_{ce}$$

- c) Energy of scattered photon depends on scattering angle θ



$$h\nu' = \frac{h\nu}{1 + \frac{h\nu}{511} [1 - \cos(\theta)]}$$

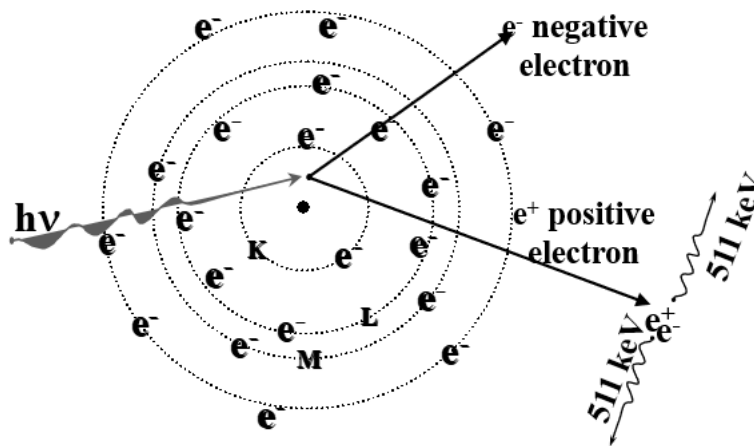
Scatter Energy Vs. Angle



Photon Energy		
θ	140 keV	511 keV
0	140	511
30	135	451
45	130	395
90	110	256
135	95	189
180	90	170

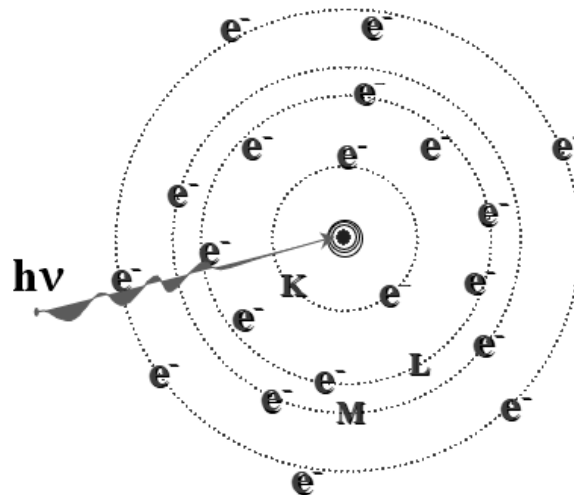
11. Pair production

- Target vicinity of nucleus with total transfer of photon energy to form a positron and electron pair
- 1022 keV threshold energy
- Kinetic energy of emitted particles: $KE_{e^+} + KE_{e^-} = h\nu - 1022 \text{ keV}$
- Secondary emission of 2 co-linear 511 keV annihilation photons



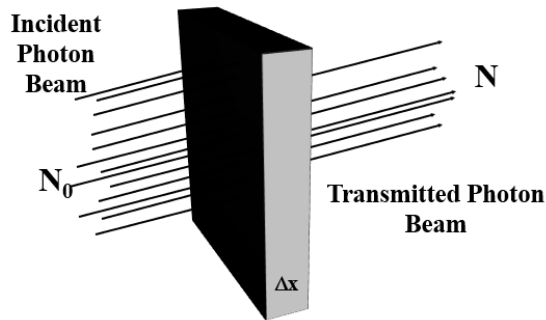
12. Photo-nuclear disintegration

- Target is Nuclear with photon totally absorbed
- May produce (γ, n) or (γ, p^+) reaction
- Prevalent only at high energies $> 10 \text{ MeV}$



13. Attenuation of Photons

Attenuation of Photons



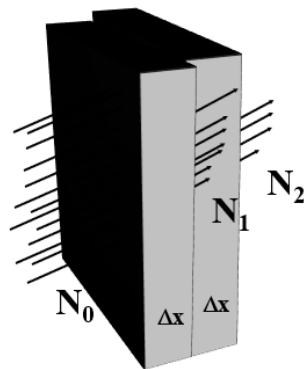
14. Transmission Fraction

Transmission Fraction

• Number of photons absorbed	$\Delta N = N_0 - N$
• Fraction of photons absorbed	$\Delta N/N_0 = \mu\Delta x$
• Linear attenuation coefficient: fraction of photons absorbed per cm of absorber	$\mu \text{ (cm}^{-1}\text{)}$
• Transmitted fraction	$1 - \mu\Delta x$
• Number of photons transmitted	$N = N_0(1 - \mu\Delta x)$

15. Transmission Through Thick Absorber

Transmission Through Thick Absorber



$$N_1 = N_0(1 - \mu\Delta x)$$

$$N_2 = N_1(1 - \mu\Delta x)$$

$$N_2 = N_0(1 - \mu\Delta x)(1 - \mu\Delta x)$$

For thick absorbers:

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

x - total thickness of
absorber in cm

16. Components of μ

$$\mu = \tau + \sigma + \kappa$$

τ	photoelectric absorption
σ	Compton absorption
κ	Pair production absorption

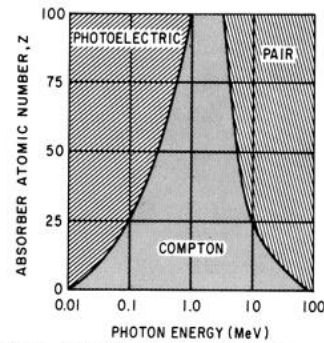


Fig. 9-8. Predominating (most probable) interaction versus photon energy for absorbers of different atomic numbers.

(From Physics in Nuclear Medicine, 2nd ed., Sorenson & Phelps, 1987, p. 189)

17. Mass Attenuation Coefficient

**Linear attenuation coefficient
normalized by absorber density**

μ/ρ	$\frac{1}{\text{cm}} / \frac{\text{g}}{\text{cm}^3}$
	$\frac{1}{\text{cm}} \cdot \frac{\text{cm}^3}{\text{g}}$
	$\frac{\text{cm}^2}{\text{g}}$

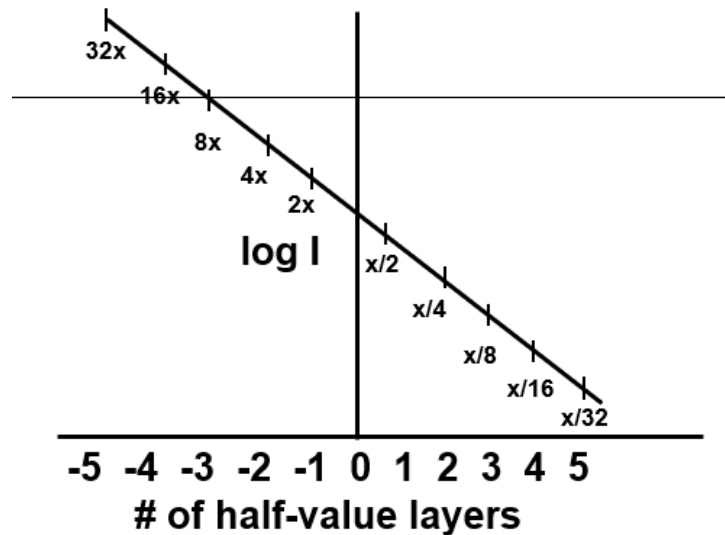
18. Half-Value Layer

**HVL = thickness of absorber required
to reduce the photon beam intensity
to one-half its initial value**

$I = I_0 e^{-\mu x}$
$I/I_0 = 1/2 = e^{-\mu(\text{HVL})}$
$\text{HVL} = 0.693/\mu$

Half-value layer: Once we know how many half-value layers are in place, we no longer care about the thickness or composition of the absorber.

- a) Which stops more Tc-99m energy, 1 HVL of Pb or one HVL of Al? Answer: The same. Absorption is directly dependent only upon # of HVLs, not the composition of the absorber. An HVL is an HVL, regardless of density or thickness.
- b) If one half value layer is placed between source and detector, beam intensity drops to $\frac{1}{2}$; for 2 half value layers, beam intensity drops to $\frac{1}{4}$; for 3 half value layers, beam intensity drops to $\frac{1}{8}$; etc.
- c) If one half value layer is removed from between source and detector, beam intensity increases by 2x; if two half value layers are removed from between source and detector, beam intensity increases by 4x; if three half value layers are removed from between source and detector, beam intensity increases by 8x



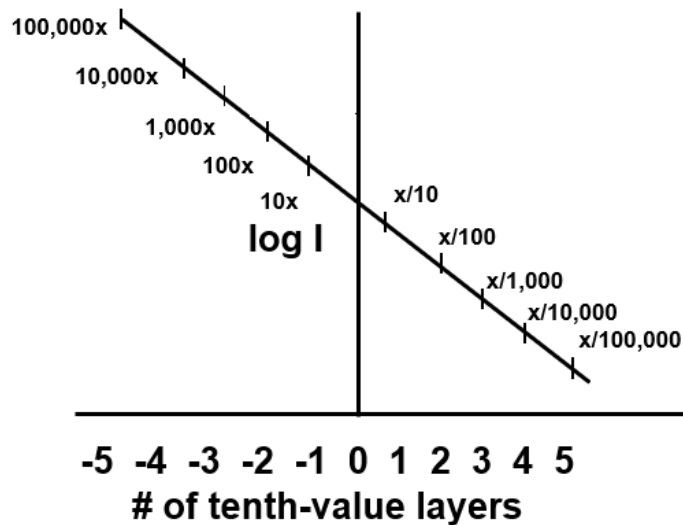
19. Tenth-Value Layer

TVL = thickness of absorber required to reduce the photon beam intensity to one-tenth its initial value

$$I/I_0 = 0.1 = e^{-\mu(\text{TVL})}$$

$$\text{TVL} = 2.30/\mu$$

- a) tenth-value layer: Once we know how many tenth-value layers are in place, we no longer care about the thickness or composition of the absorber.
- b) Which stops more Tc-99m energy? 1 TVL of Pb or one TVL of Al? Answer: the same. 2 HVL of Pb or one TVL of Al? Answer: TVL of Al
- c) If one tenth value layer is placed between source and detector, beam intensity drops to 1/10; for 2 tenth value layers, beam intensity drops to 1/100; for 3 tenth value layers, beam intensity drops to 1/1000, etc.
- d) If one tenth value layer is removed from between source and detector, beam intensity increases by 10x; if two tenth value layers are removed from between source and detector, beam intensity increases by 100x; if three tenth value layers are removed from between source and detector, beam intensity increases by 1,000x



20. Comparative Chart.

- a) Note that nothing related to radiation is linear. Everything decreases logarithmically rather than linearly.
- b) In a comparison between 4 HVLs and 4 TVLs, note that the 4 TVLs are 625 times as effective as 4 HVLs.

Layers	Intensity		
	HVL	TVL	LINEAR
0	1,000	1,000	1,000
1	500	100	500
2	250	10	0
3	125	1	----
4	62.5	0.1	----

21. HVL in Water & TVL in Lead

Radionuclide	Energy (keV)	HVL in Water (cm)	TVL in Lead (mm)
^{125}I	27.5	1.7	0.06
^{133}Xe	81	4.3	1.0
$^{99\text{m}}\text{Tc}$	140	4.6	0.9
^{131}I	364	6.3	7.7
^{18}F	511	7.1	13.5
^{60}Co	1330	11.2	36.2

22. Radiation Detectors

a) Directly or indirectly measure the ionization produced by the radiation interaction.

b) Examples

- i. Radiographic and photographic film
- ii. Gas ionization chamber
- iii. Luminescent scintillators (indirectly measure ions by emitting light)
 1. Thermal
 2. Liquid
 3. Solid
- iv. Solid-state diodes

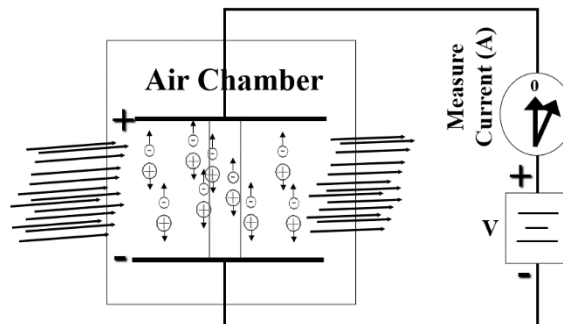
23. Radiographic and photographic film

- a) Silver-halide film is sensitive to radiation interactions
- b) Developed film density is proportional to the total radiation absorbed dose
- c) Film badge used to monitor the radiation absorbed dose received by the technologist.

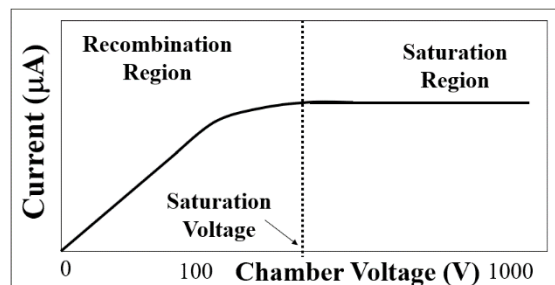
24. Gas ionization chamber

- Instrument designed to directly measure the ionization in a gas (air) during radiation exposure.
- The electric charge produced is proportional to the intensity of the radiation, and the radiation absorbed dose in the gas.
- The radiation absorbed dose in the gas can be extrapolated to dose in a patient.

Instrument designed to measure ionization in a gas (air) during radiation exposure.



Ion Chamber Saturation Voltage

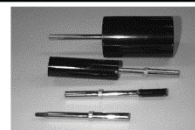


The “saturation voltage” ensures that all ions produced by the x-ray or γ -ray beam are collected, thus achieving maximum sensitivity of the chamber to the radiation.

25. Saturation Region Ionization Chambers

- Survey Meter – meter to conduct radiation surveys

Survey Meters



Sealed Air Chamber enclosed at bottom of meter

- Larger Air Chamber has greatest sensitivity
- Unsealed chambers require air pressure correction
- Meters calibrated annually

- b) Personnel pocket dosimeters

Pocket Dosimeters



- Integrating dose meter used by personnel for short term monitoring
- Ion chamber electrodes charged fully before use, and total exposure (or dose) is determined by the amount of discharge of the electrodes in the chamber

- c) Automatic exposure control (AEC) in x-ray imaging systems
 d) Dose Calibrator – measure radioactive dosages for patients

Dose Calibrators



- Ion Chamber used to assay radioactivity of radioisotope
 Uses Specific Gamma Ray Constant:
 $\Gamma_{\text{isotope}} = X \text{ Rad} \cdot \text{cm}^2/(\text{hr} \cdot \text{mCi})$
 Γ_{isotope} – values tabulated for every isotope
- Dose calibrator calibrated for each isotope daily

26. Roentgen - Unit of Exposure

- An exposure of 1 Roentgen corresponds to the production of ions by x-rays, gamma rays, & charged particles in air to an amount equal to
- $1 \text{ R} = 2.58 \times 10^{-4} \text{ Coulomb/Kg air}$
- Equivalent of 2×10^9 ion pairs produced per cc air
- Exposure rate is measured in terms of R/hr
- Roentgen is a large unit. Most radiation surveys measure exposure in terms of mR.

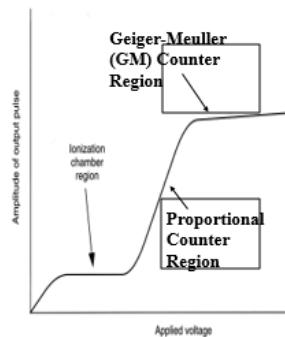
27. Air Kerma

Air Kerma

- **Kinetic energy released per unit mass (air) by ionizing radiation.**
- **Radiation absorbed dose in air directly without reference to Exposure.**
- **Ion chambers calibrated in Gray not Roentgens.**

28. Higher Collecting Voltages

Higher Collecting Voltages



- **Increasing electrode voltages over 1000 V, causes gas amplification**
- **Gas amplification permits counting of single particles in the Proportional Counter Region**
- **Complete gas ionization occurs in the Geiger-Mueller Region**

29. Types of Gas Amplification Chambers

Types of Gas Amplification Chambers

Proportional Counter

- **Device counts particle (neutrons, betas, gammas) emitted from nuclear reactors and cyclotrons**

Geiger Counter

- **Device counts particles emitted from radioactive sources (beta and gamma)**
- **Surveys for radioactive contamination of surfaces**

Geiger Counters

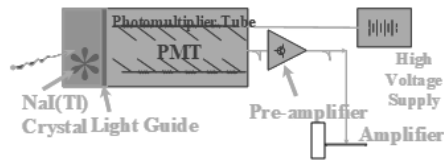


- Counts γ -ray, beta, and alpha particles that enter the gas chamber
- Thin mica window, with a thickness of 2.0 mg/cm^2 , allows detection of beta particles in excess of 35 keV and γ -rays greater than 6 keV
- Chamber sealed with an inert gas and with a halogen quenching gas to stop UV production
- Count rate limited by $100 \text{ }\mu\text{sec}$ dead time (maximum 10^4 counts/sec.)
- Count rate converted to exposure – calibrated for 600 keV γ -rays; limited to 100 mR exposure rates.

30. Solid Scintillation Counter

Solid Scintillation Counter

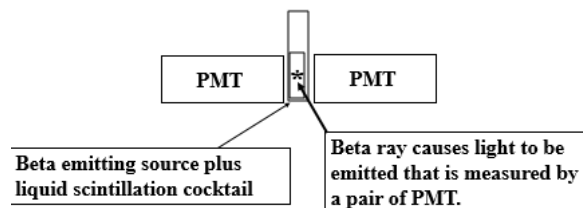
- Counts individual photon (X-ray or Gamma ray) interactions.
- The scintillation crystal emits light following an interaction.
- Interaction of a selected energy is counted.



31. Liquid Scintillation Counter

Liquid Scintillation Counter

- Measures the ionization produced by beta and alpha rays.
- The radioactive source is mixed in with the liquid scintillator (ions produced causes light to be emitted)
- Each interaction of a selected energy range is counted.



32. Liquid Scintillation Cocktail

Liquid Scintillation Cocktail

Has three components:

- 1) Radioactive sample
- 2) Organic liquid solvent
- 3) Organ liquid fluor

Cocktail is the mixture of the organic solvent and fluor into which the radioactive sample is mixed.

Common cocktails include toluene as a solvent and a fluor mixture called POP and POPOP

33. Beta Emission Spectrum

Beta Emission Spectrum

Energy spectrum of a beta emitter exhibits a continuum of beta energies from zero to β_{\max} .

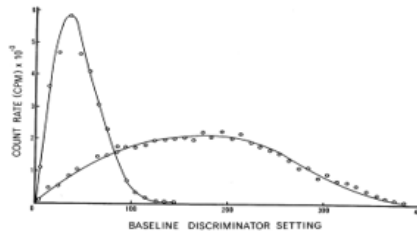


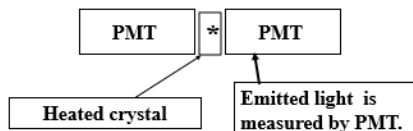
Figure 15-12 Pulse-height spectra for ³H and ¹⁴C in toluene measured with a liquid scintillation counter with logarithmic amplification.

β_{\max} ³H – 18.3 keV
 β_{\max} ¹⁴C – 156 keV

34. Thermal-luminescent Scintillation Detector; Thermal Luminescent Dosimeter (TLD)

Thermal Luminescent Scintillation Detector

- A solid crystal of LiF stores the energy of ionization.
- The absorbed energy is released as visible light when the crystal is heated to 400 degrees.
- The light intensity that corresponds to the total energy absorbed.



Thermal Luminescent Dosimeter (TLD)

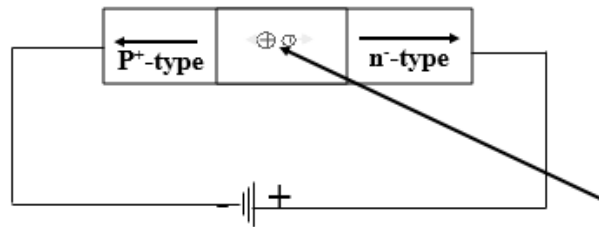
- LiF crystal placed on or in subject during irradiation. Taken to TLD reader to measure the light output and dose.
- The ring badge radiation monitor contains a TLD to measure the radiation dose to the hands.

35. Solid-State Detectors

- a) No PMT required.
- b) Liquid nitrogen temperature operated detectors of GeLi; energy resolution $< 1\%$.
- c) Room temperature operated detectors of cadmium-zinc and cadmium zinc telluride (CZT); energy resolution $< 6\%$.

Solid-State Semi-Conductor Diodes

Measures ions produced by the radiation interaction in reverse-biased electric diodes.



Ions produced by the photon interaction are collected at the p+-type and n-type ends. Total charge collected is proportional to energy of the photon.