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** –

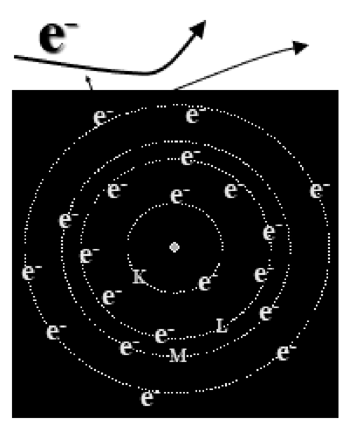
i. Energetic uncharged particles that ionize atoms and molecules in an absorbing medium:
ii. Collide with and deliver energy to charged particles in the absorbing medium, which in turn produce ionization.
iii. Examples: gamma rays, x-rays, & neutrons.

2. Coulombic Collisions

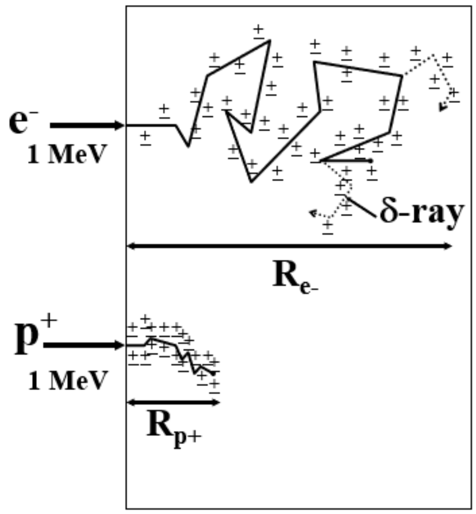
a) Collision between charged particles involve the Coulombic force of attraction and repulsion, rather than actual contact.

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**



- **Bombarding particle produces ionization (±) tracks until it stops.**
- **Secondary ionization tracks are called δ-rays**
- **The depth of the track is the particle range (R)**

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

   a) Particle kinetic energy - The higher its kinetic energy, the greater its range.

   b) Particle mass - Lighter particles of the same kinetic energy have greater range, due to its higher velocity ($v=1/2mv^2$)

   c) Particle charge - Particles with less charge have greater range. Its range is inversely proportional to the square of its charge.

   d) 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)

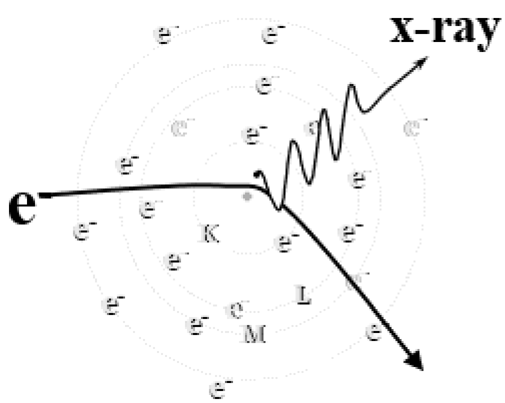
	Air		Soft Tissue	
Energy (keV)	e^- or e^+	α	e^- or e^+	α
10	1.6	0.10	0.002	<.0001
100	160	1.0	0.2	0.0014
1,000	3,300	5.0	4.0	0.0072
10,000	41,000	105	50	0.1400

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); $h\nu > 1022$ keV	Z	ρ

8. Thompson/Raleigh/Coherent Scattering

a) Target is with whole atom; No energy transfer: $h\nu' = h\nu$

b) Prevalent only at low energies < 10 keV

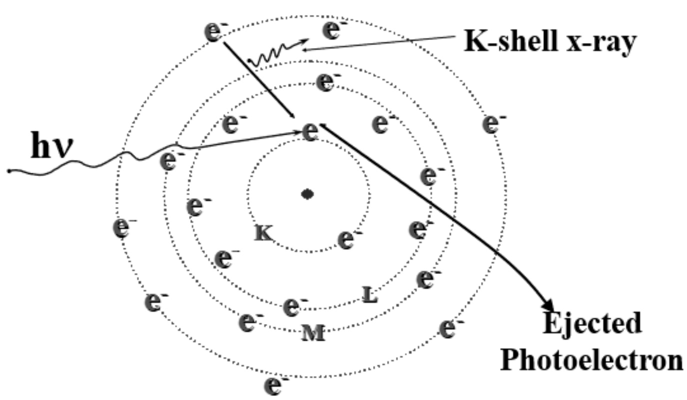
9. Photoelectric effect

a) K-shell is primary target

b) Total transfer of photon energy to orbital electron

c) Kinetic energy of photoelectron = $KE_{PE} = h\nu$ - Binding Energy

d) Secondary emission of K-shell x-ray or Auger electron



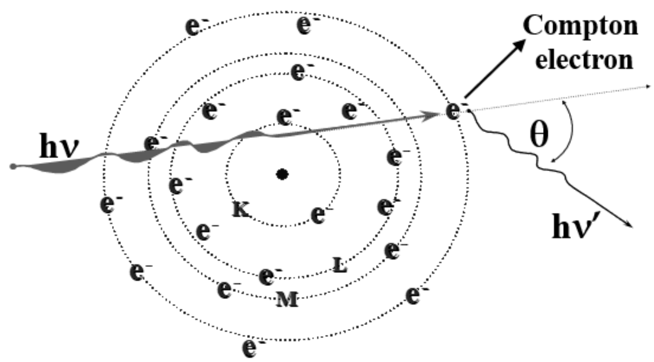
10. Compton scattering

a) Outer-shell electrons are primary target

b) Energy transfer shared between Compton electron and scattered photon

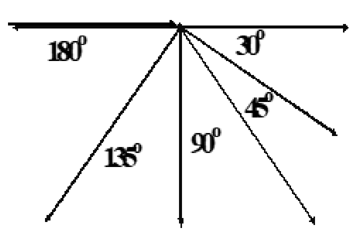
$$h\nu = h\nu' + KE_{ce}$$

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

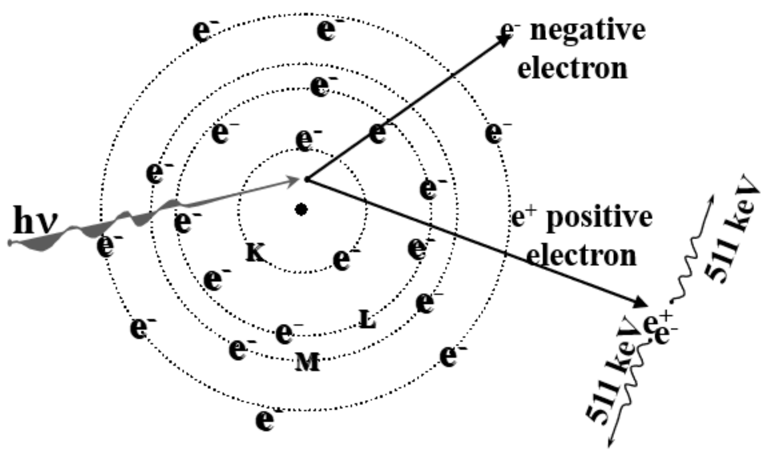
11. Pair production

a) Target vicinity of nucleus with total transfer of photon energy to form a positron and electron pair

b) 1022 keV threshold energy

c) Kinetic energy of emitted particles: $KE_{e+} + KE_{e-} = h\nu - 1022$ keV

d) Secondary emission of 2 co-linear 511 keV annihilation photons

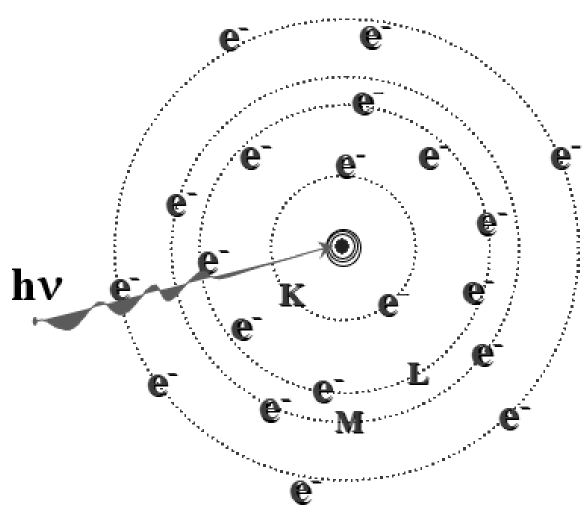


12. Photo-nuclear disintegration

a) Target is Nuclear with photon totally absorbed

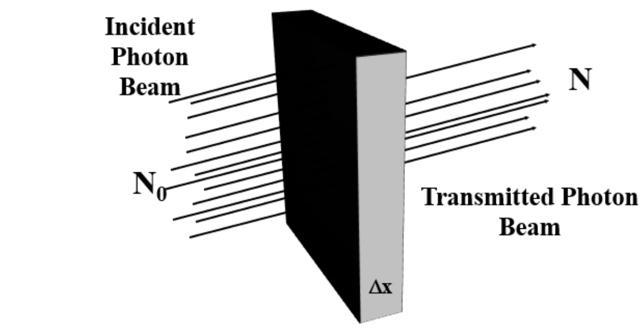
b) May produce (γ,n) or (γ,p+) reaction

c) Prevalent only at high energies > 10 MeV



13. Attenuation of Photons

Attenuation of Photons



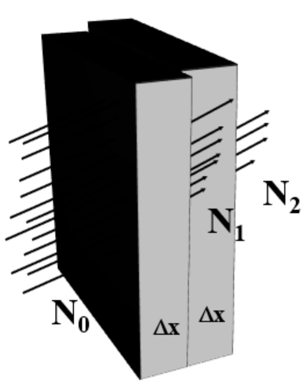
14. Transmission Fraction

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	μ (cm^{-1})
• 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**

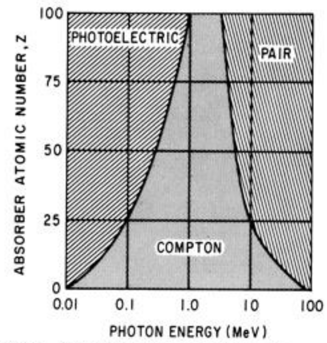


Fig. 9-8. Predominating (most probable) interaction versus photon energy for absorbers of different atomic numbers.

(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

$$I = I_0 e^{-\mu x}$$

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

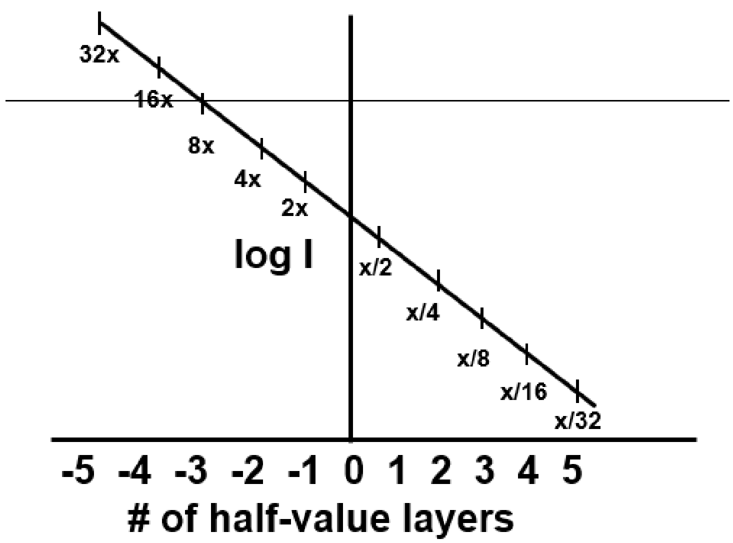
$$\text{HVL} = 0.693/\mu$$

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 ½; for 2 half value layers, beam intensity drops to ¼; for 3 half value layers, beam intensity drops to ⅛; 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

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

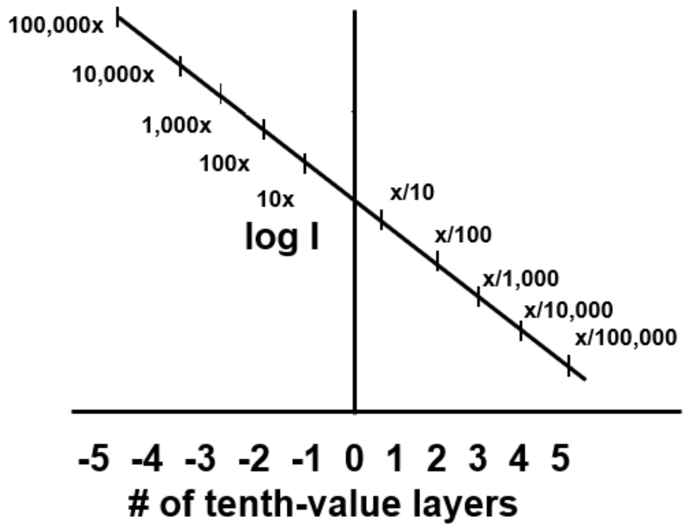
$$TVL = 2.30/\mu$$

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 than 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.

Intensity

Layers	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
^{99m}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

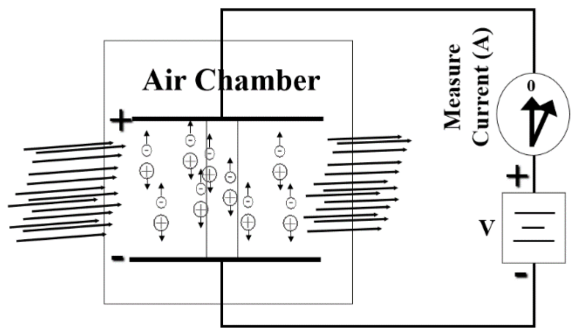
b) Developed film density is proportional to the total radiation absorbed dose

c) Film badge used to monitor the radiation absorbed dose received by the technologist.

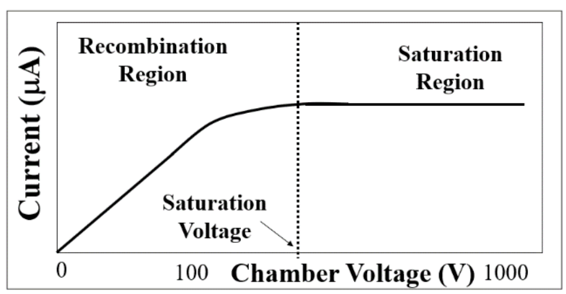
24. Gas ionization chamber

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

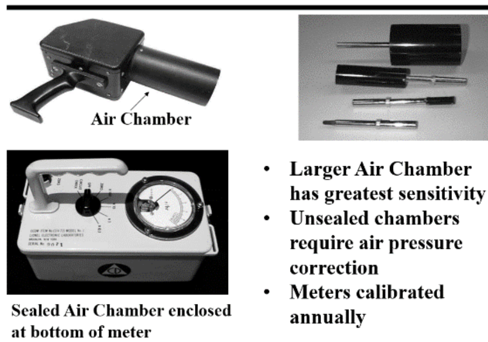


The "saturation voltage" ensures that all ions produced by the x-ray or γ-ray beam are collected, thus achieving maximum sensitivity of the chamber to the radiation.

25. Saturation Region Ionization Chambers

a) Survey Meter – meter to conduct radiation surveys

Survey Meters



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:
  $\Gamma_{isotope}$ = X Rad · cm²/(hr · mCi)

  $\Gamma_{isotope}$ – values tabulated for every isotope
- **Dose calibrator calibrated for each isotope daily**

26. Roentgen - Unit of Exposure

a) 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

b) 1 R = 2.58×10^{-4} Coulomb/Kg air

c) Equivalent of 2×10^{9} ion pairs produced per cc air

d) Exposure rate is measured in terms of R/hr

e) Roentgen is a large unit. Most radiation surveys measure exposure in terms of mR.

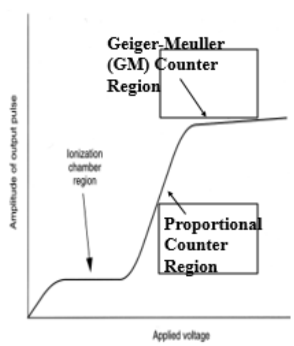
27. Air Kerma

Air Kerma

- ***K**inetic **e**nergy **r**eleased per unit **ma**ss (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**

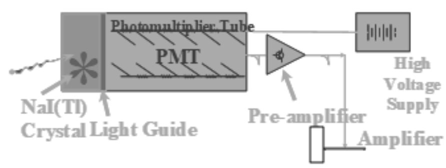
Geiger Counters

- Counts γ-ray, beta, and alpha particles that enter the gas chamber
- Thin mica window, with a thickness of 2.0 mg/cm², 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 μsec 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

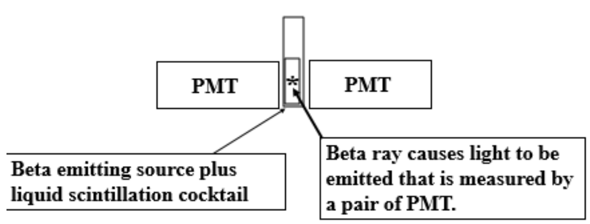
- Counts individual photon (X-ray or Gamma ray) interactions.
- The scintillation crystal emits light following an interaction.
- Interaction of a selected energy is counted.



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 flour 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}.

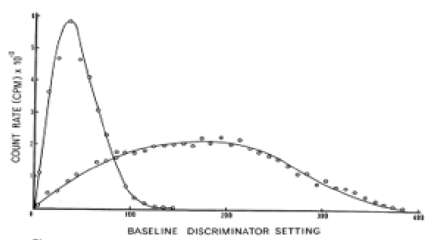


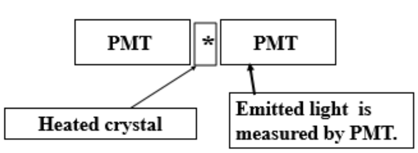
Figure 15-12 Pulse-height spectra for ^3H and ^{14}C in toluene measured with a liquid scintillation counter with logarithmic amplification.

β_{max} ^3H – 18.3 kev
β_{max} ^{14}C – 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%.