

5: Emission (Computed) Tomography

1. What is a tracer ?
2. Why is collimation necessary and what are its consequences ?
3. How are the effects of attenuation taken into account ?
4. What is the principle of x-ray detection ?
scintillation
5. How are scintillation photons converted to an electrical signal ?
6. How can scattered photons be eliminated ?

After this course you

1. Understand the reason for collimation in imaging γ -emitting tracers and its implication on resolution/sensitivity
2. Understand the implications of x-ray absorption on emission tomography
3. Understand the basic principle of radiation measurement using scintillation
4. Are familiar with the principle/limitations of photomultiplier tube amplification
5. Understand the use of energy discrimination for scatter correction

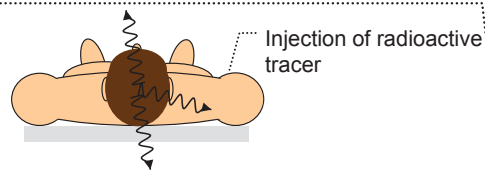
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5-1

What is Emission Computed Tomography ?

Until now: CT and x-ray imaging measure attenuation of incident x-ray

Emission tomography: X-rays emitted by exogenous substance (tracer) in body are measured



Two issues:

1. How to determine directionality of x-rays ?
2. Absorption is undesirable

What is a tracer ?

Exogenously administered substance (infused into blood vessel) that

- (a) alters image contrast (CT, MRI)
- (b) has a unique signal (γ emitting)

-> **Emission** computed tomography

Typical tracers for emission tomography

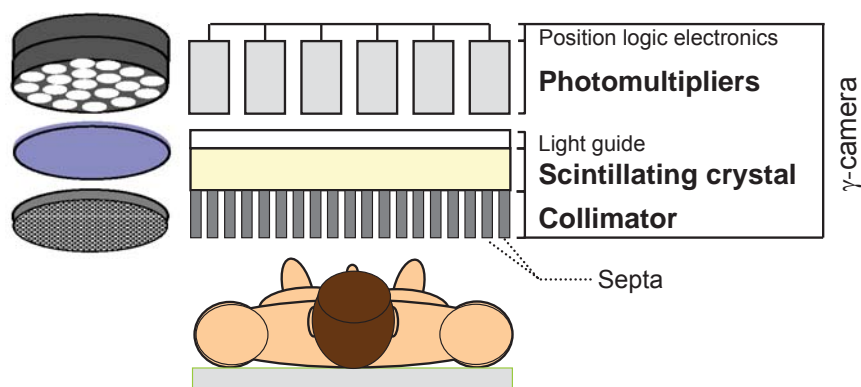
half-life and photon energies

	[h]	[keV]
^{99m}Tc	6	140
^{201}Tl	73	70
^{123}I	13	159
^{133}Xe	0.08	81

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5-4

What are the basic elements needed for γ -emitter imaging ?

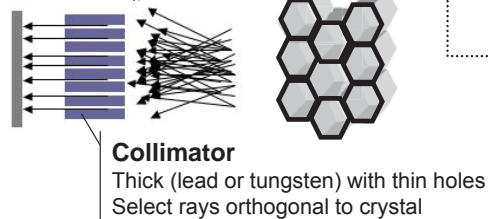
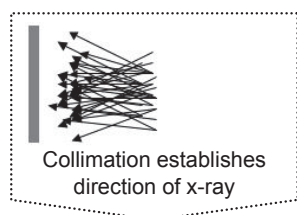


5-2. How can directionality of x-rays be established ?

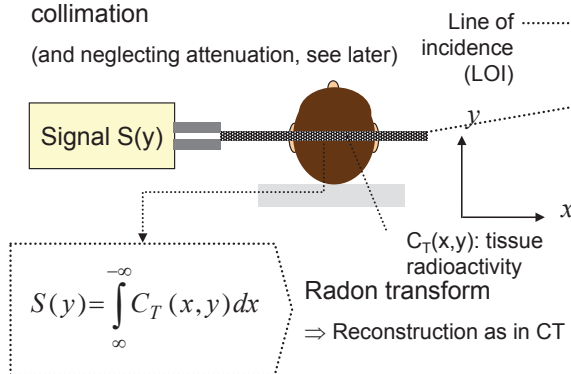
Collimation

Problem: Photon detection alone does not give directionality

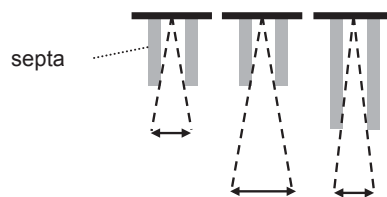
Solution:



Consider one detector, assuming perfect collimation (and neglecting attenuation, see later)



Impact of collimation on resolution



How does collimation affect resolution ?

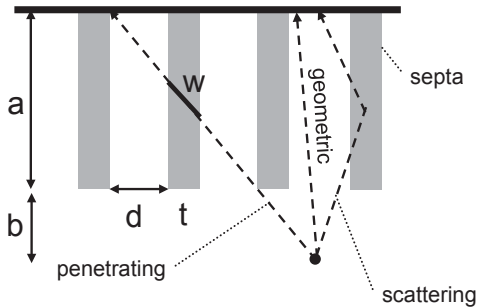
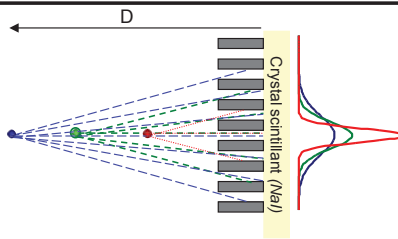
It's never perfect ...

Perfect collimation, i.e. resolution ?

$$d/a \rightarrow 0$$

$$\mu_{\text{collimator}} t \rightarrow \infty$$

Impossible to achieve (Why?)



Septa penetration < 5% occurs when $t=t_{5\%}$:

$$t_{5\%} \approx \frac{6d/\mu}{a-3/\mu}$$

Collimator resolution:

Two objects have to be separated by distance $> R$

$$R = \frac{d(a_e + b)}{a_e}$$

$$a_e = a - 2/\mu$$

(a_e : imperfect septal absorption)

Price of collimation (resolution) ?

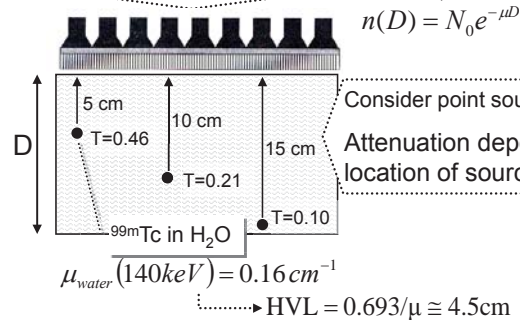
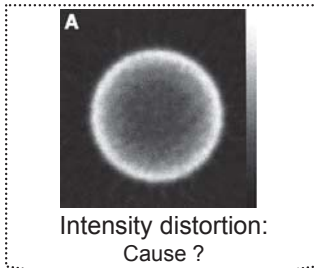
Sensitivity !

5-7

5-3. How to deal with attenuation of the emitted x-rays ?

result of x-ray absorption in tissue

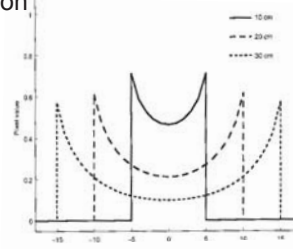
Signal measured from a homogeneous sphere ($C_T(x,y)=\text{constant}$)



Attenuation T

$$T = \frac{n(D)}{N_0} = e^{-\mu D}$$

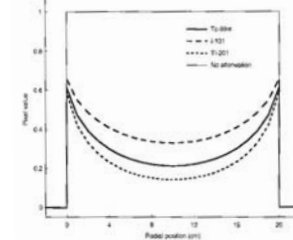
1. depends on object dimension and source location ($D=f(\text{object})$)



Consider point source:

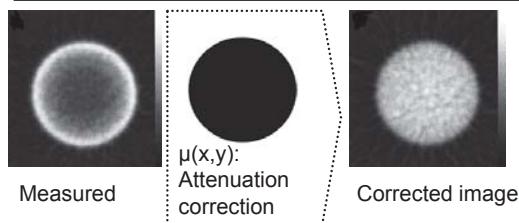
Attenuation depends on location of source in tissue

2. Photon energy $\mu=f(E_\gamma)$



5-8

What are the basic steps in attenuation correction ?



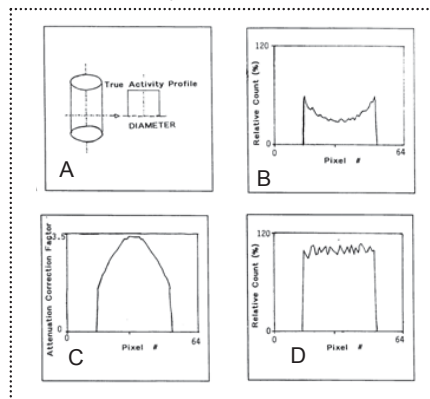
Attenuation correction procedure

- Estimated object geometry and estimated $\mu(x,y)$ or measured $\mu(x,y)$
- Transmission loss : $T(\text{projection}) = f(\mu(\text{object}), \text{projection})$
- Attenuation correction $A(x,y) = 1/T(x,y)$
- Corrected $C_{\text{corr}}(x,y) = A(x,y) C(x,y)$

Problem is prior knowledge needed for A (i.e. $\mu(x,y)$)

Attenuation correction rarely applied!

$A(x,y)$ of thorax

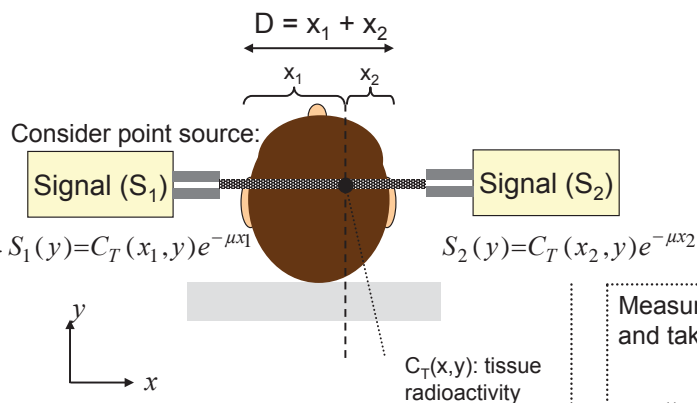


5-9

How to simplify attenuation correction ?

by measuring at 180° using geometric mean

Problem: Spatial dependence of correction



$$\sqrt{S_1 \cdot S_2} = C_T(x, y) e^{-\mu D / 2}$$

NB. This correction can be used in emission tomography for focal uptake (i.e. uptake limited to a specific region)

Measure at 180° simultaneously and take the geometric mean

→ attenuation correction depends only on dimension of object along the measured Radon transform

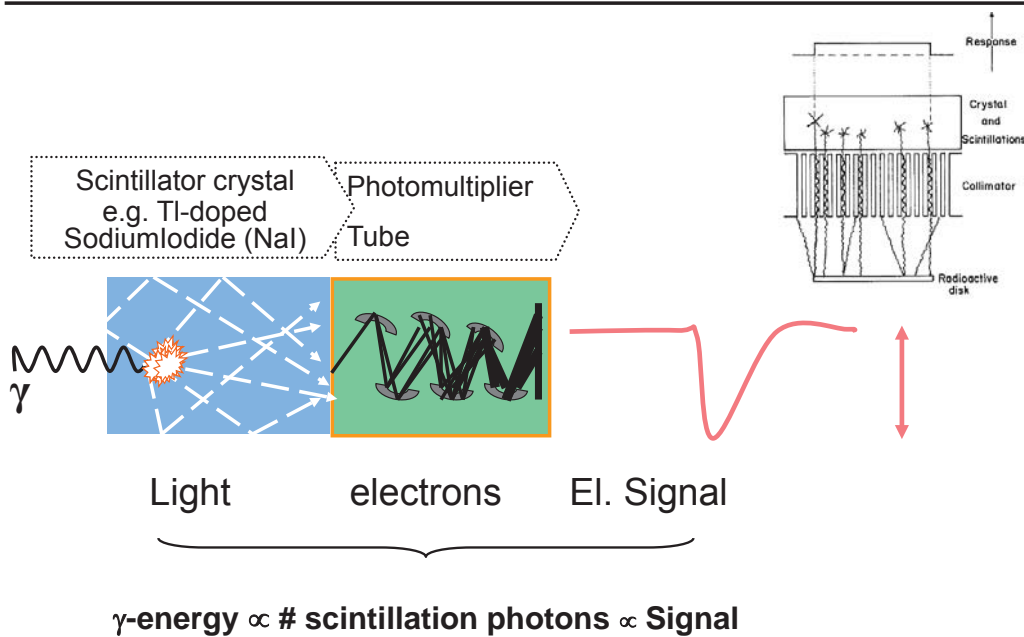
Solution: Geometric mean of the two 180° opposite signals:

$$\begin{aligned} \sqrt{S_1 \cdot S_2} &= \sqrt{C_T(x_1, y) e^{-\mu x_1} C_T(x_2, y) e^{-\mu x_2}} \\ &= C_T(x, y) \sqrt{e^{-\mu(x_1 + x_2)}} = C_T(x, y) \sqrt{e^{-\mu D}} \quad (D = x_1 + x_2) \end{aligned}$$

5-10

5-4. What is the principle of x-ray detection ?

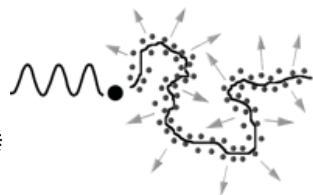
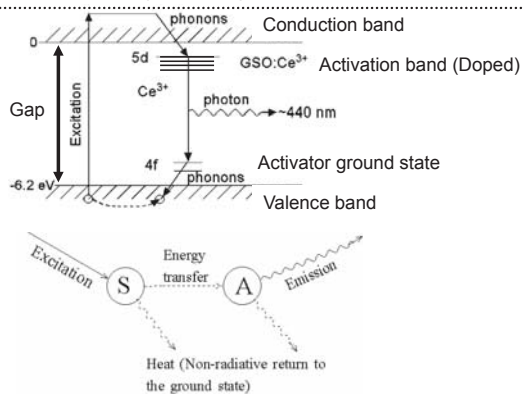
Collimation, followed by scintillation and amplification



What is Scintillation ?

Sequence of events in scintillation crystal

1. Atom ionized by Compton interaction → Electron-hole pair
2. Hole ionizes activator, electron falls into activator
3. Activator is deactivated by emission of Photons (10^{-7} sec)



Gamma Ray
Primary Fast e⁻
Excited Secondary e⁻
Scintillation Photon

Efficiency of scintillators

$$\eta \equiv \frac{\text{energy of scintillation light}}{\text{energy deposited}} \propto \frac{Tq_a}{W_{e-h}}$$

T = energy transfer efficiency from excited ion to luminescence centre

q_A = quantum efficiency of luminescence centre

W_{e-h} = energy required to create one electron-hole pair

What elements characterize scintillation materials ?

Overview of some crystals

Scintillator	Density (g/cm ³)	Attenuation Coefficient (cm ⁻¹ @ 511 keV)	Light yield ph/keV	λ (nm)	τ (ns)	Z_{eff}	Refr. Index	Yield
CdWO ₄	7.90	0.886	19	495	$\sim 10^4$	73	2.15	13%
Bi ₄ Ge ₃ O ₁₂	7.13	0.964	8	480	300			
(Y,Gd) ₂ O ₃ :Eu,Pr	5.9	0.503 - 0.637	19	610	$\sim 10^6$			
Gd ₂ O ₂ S:Pr,Ce,F	7.34	0.786	40	510	$\sim 10^3$			
NaI:Tl	3.67	0.343	40	415	230	51	1.85	100%
Gd ₂ SiO ₅ :Ce	6.71	0.704	7	430	300	59		
Lu ₂ SiO ₅ :Ce	7.4	0.869	30	420	40	66		79%
LuAlO ₃ :Ce	8.34	0.956	11	365	~ 17			
LuPO ₄ :Ce	6.53	0.735	17	360	25			

Requirements for scintillator

- High yield
- Good linearity
- Small time constant τ
- Transparent for scintillation light λ
- good mechanical properties
- Refraction index close to 1.5

Most of the energy of the x-ray is lost as heat (to lattice), see

e.g. NaI(140keV)=40-140
=5600 photons at $\lambda=400\text{nm}$

$$E_{400\text{nm}}[\text{keV}] = hc/\lambda = 1.2/\lambda [\text{nm}]$$

$$= 1.2/400 \text{ keV} = 3\text{eV}$$

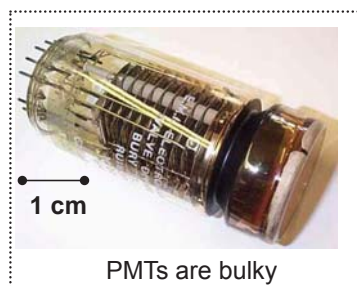
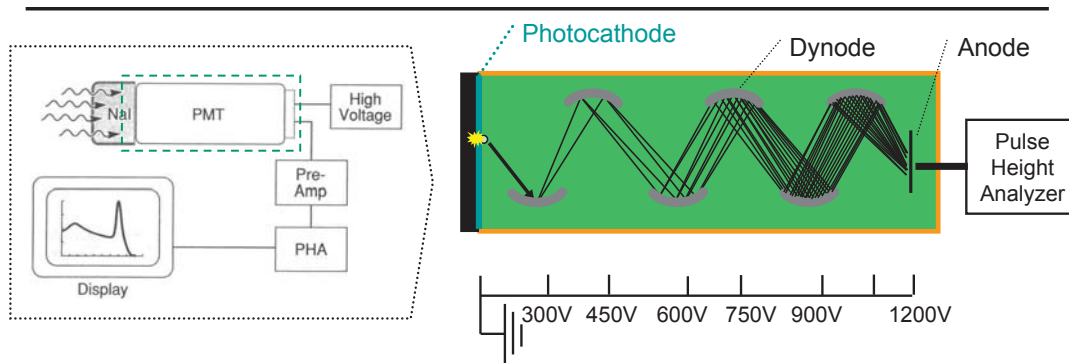
<20keV
or <120eV/keV

5-13

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5-5. How is the scintillation light converted to an electrical signal ?

Photomultiplier tube (PMT) -Noiseless amplification



How to increase resolution beyond PMT dimensions ?

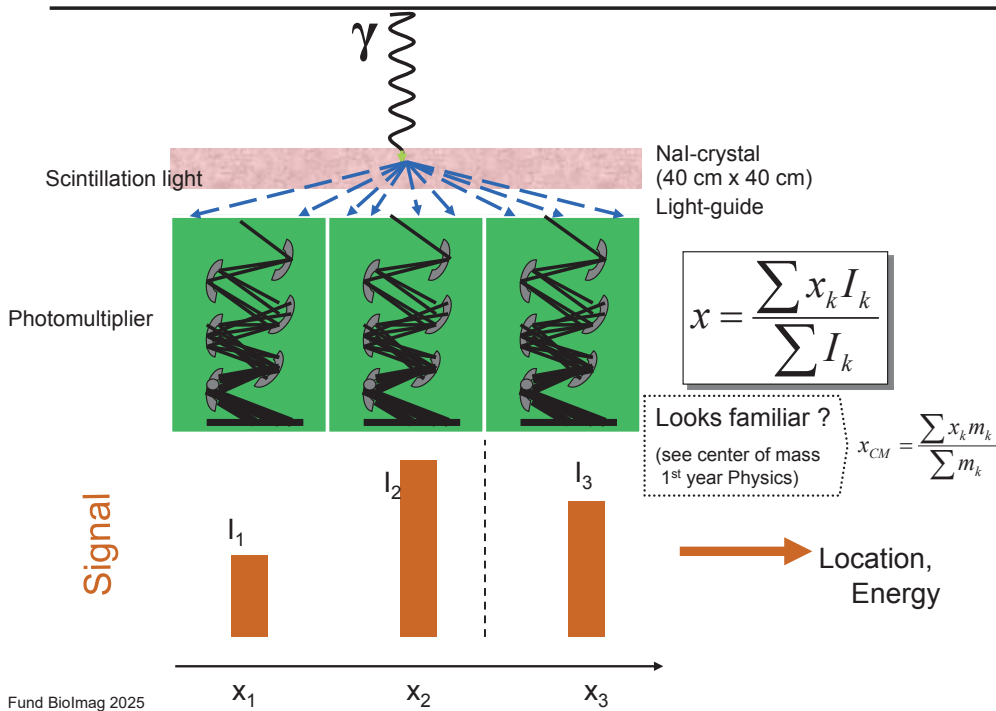
Scintillator crystal

5-14

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How to improve the spatial resolution of PMT ?

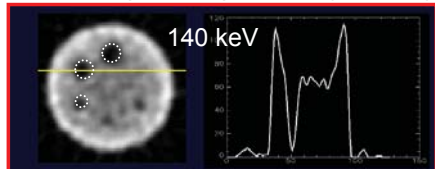
(Anger, 1964)



5-15

5-6. How to discriminate scattered photons ?

Tc-99m spherical phantom (w. holes)



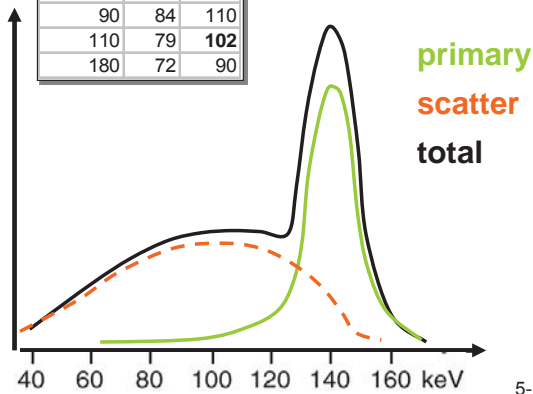
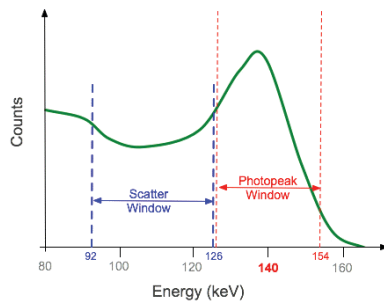
Most scattering is by Compton

$$E_f = \frac{E_i}{1 + E_i \frac{(1 - \cos \theta)}{m_e c^2}}$$

Measure E_f
→ identify severely
scattered photons

theta/ E_i	100	140
20	99	138
45	95	130
90	84	110
110	79	102
180	72	90

Intensity

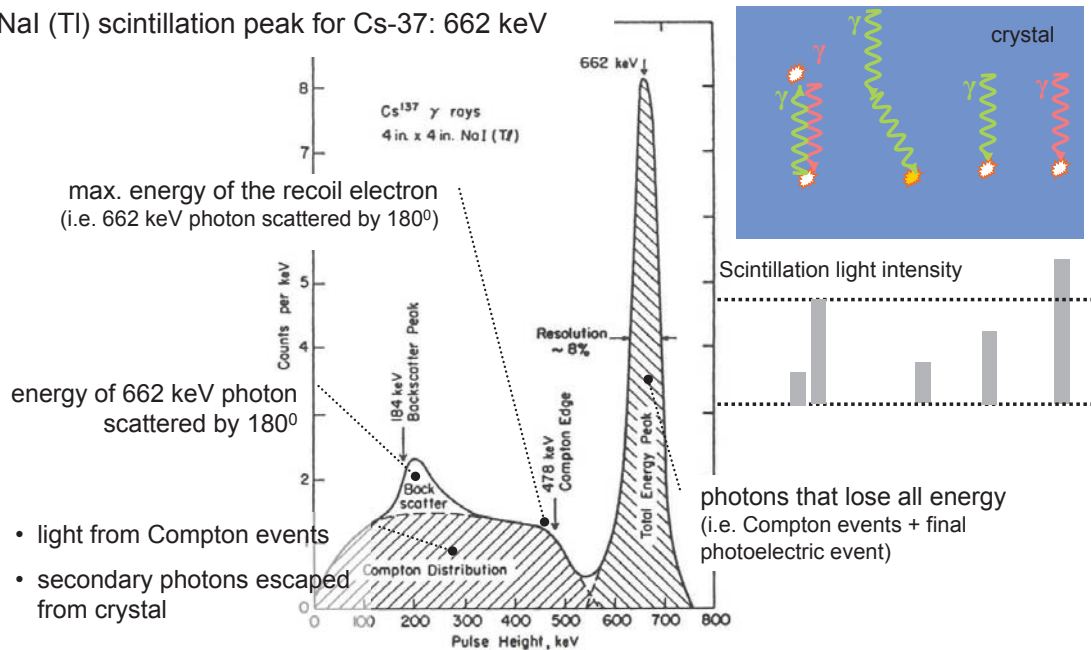


5-16

What processes contribute to the Scintillation light spectrum ?

scintillation signal depends on x-ray energy

NaI (TI) scintillation peak for Cs-37: 662 keV



SPECT summary

Single Photon Emission Computed Tomography

1. Measurement of single photon emitters injected into subject
2. Collimation ensures x-ray directionality (\Rightarrow backprojection)
3. Absorption is undesirable
4. Photon energies comparable to CT \Rightarrow SPECT-CT