

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

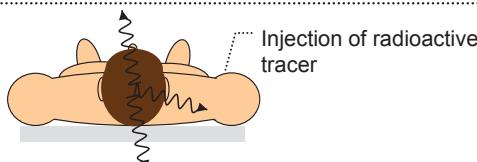
1. Understand the reason for collimation in imaging γ -emitting tracers and its implication on resolution/sensitivity
2. Understand the implications of x-ray absorption on emission tomography
3. Understand the basic principle of radiation measurement using scintillation
4. Are familiar with the principle/limitations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

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

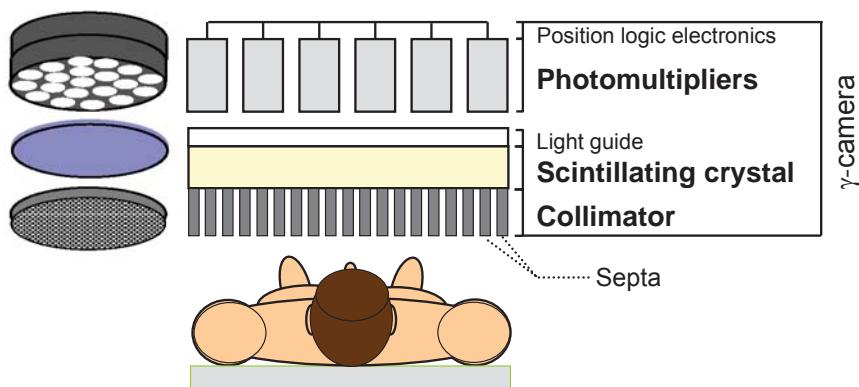
Typical tracers for emission tomography

half-life and photon energies

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

5-4

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



5-5

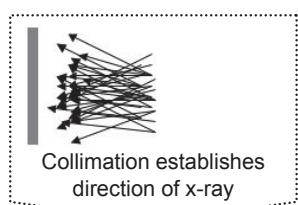
Fund Biolmag 2025

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

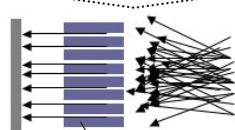
Collimation

Problem: Photon detection alone does not give directionality

Solution:

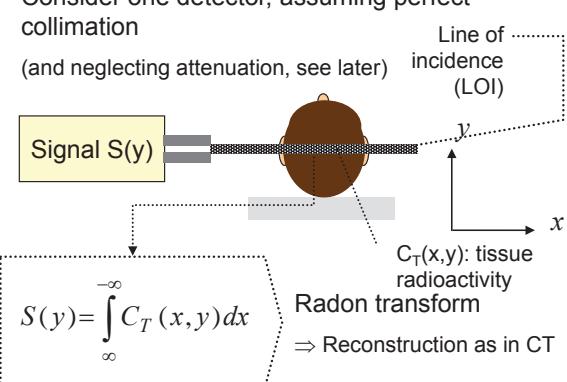


Collimation establishes direction of x-ray

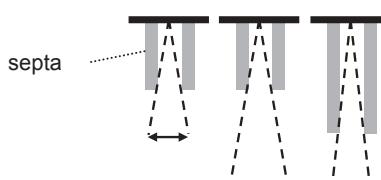


Collimator
Thick (lead or tungsten) with thin holes
Select rays orthogonal to crystal

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



Impact of collimation on resolution



5-6

Fund Biolmag 2025

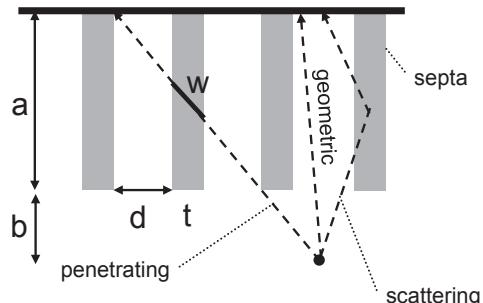
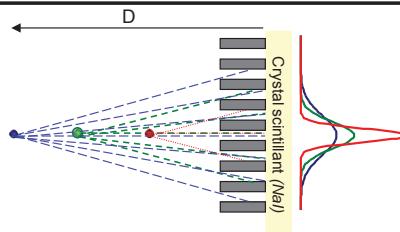
How does collimation affect resolution ?

It's never perfect ...

Perfect collimation, i.e. resolution ?

$$\begin{aligned} d/a &\rightarrow 0 \\ \mu_{\text{collimator}} t &\rightarrow \infty \end{aligned}$$

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 !

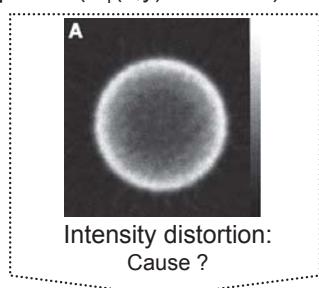
5-7

Fund Biolmag 2025

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

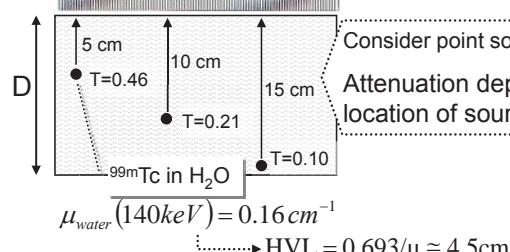
result of x-ray absorption in tissue

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



Intensity distortion: Cause ?

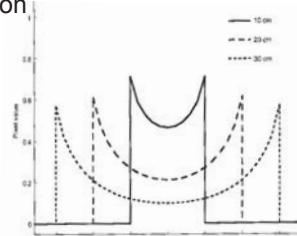
$$n(D) = N_0 e^{-\mu D}$$



Attenuation T

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

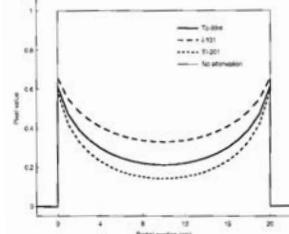
1. depends on object dimension and source location ($D=f(\text{object})$)



Consider point source:

Attenuation depends on location of source in tissue

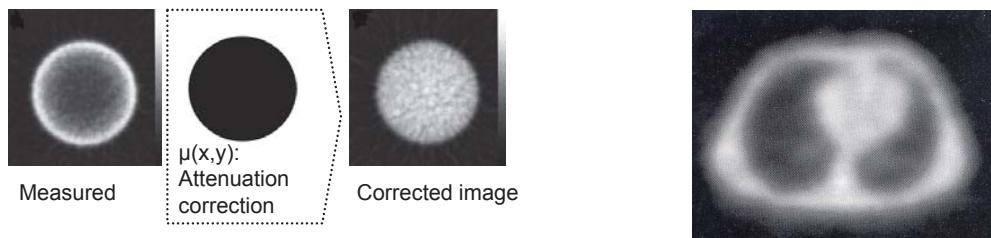
2. Photon energy $\mu=f(E_\nu)$



5-8

Fund Biolmag 2025

What are the basic steps in attenuation correction ?

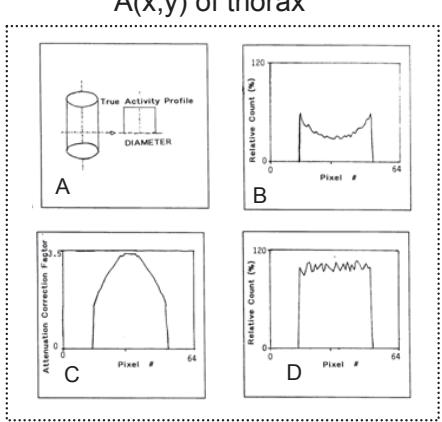


Attenuation correction procedure

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



5-9

How to simplify attenuation correction ?

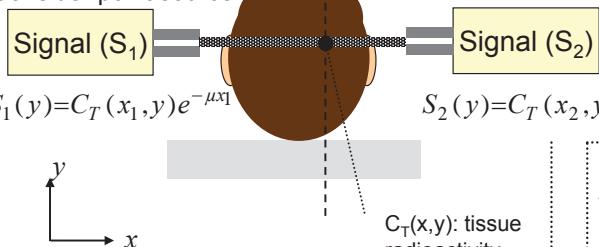
by measuring at 180^0 using geometric mean

Problem: Spatial dependence of correction

$$D = x_1 + x_2$$

x_1 x_2

Consider point source:



$$S_1(y) = C_T(x_1, y) e^{-\mu x_1}$$

$$S_2(y) = C_T(x_2, y) e^{-\mu x_2}$$

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

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

Measure at 180^0 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 180^0 opposite signals:

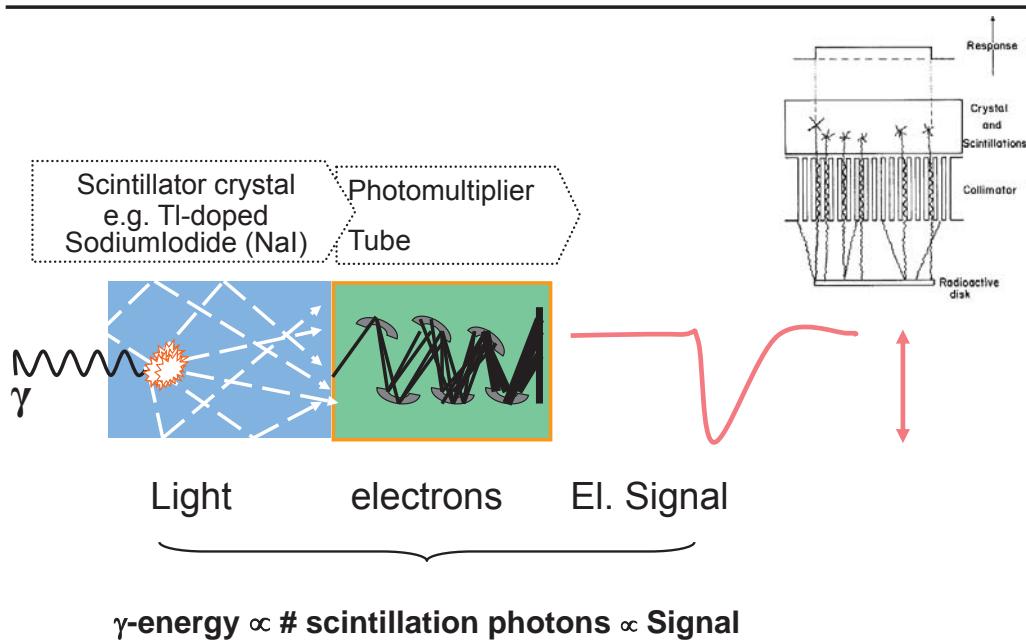
$$\sqrt{S_1 \cdot S_2} = \sqrt{C_T(x_1, y) e^{-\mu x_1} C_T(x_2, y) e^{-\mu x_2}}$$

$$= C_T(x, y) \sqrt{e^{-\mu(x_1+x_2)}} = C_T(x, y) \sqrt{e^{-\mu D}} \quad (D = x_1 + x_2)$$

5-10

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

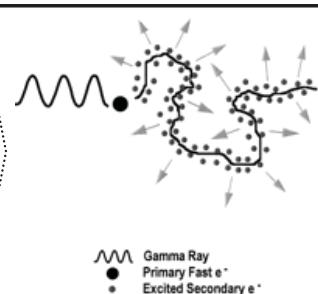
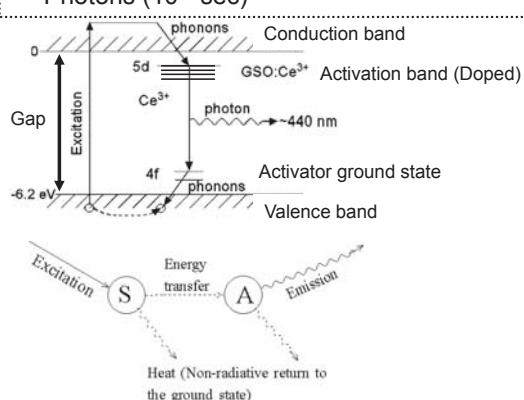
Collimation, followed by scintillation and amplification



What is Scintillation ?

Sequence of events in scintillation crystal

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



Efficiency of scintillators

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

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	$\sim 10^4$			
Bi ₄ Ge ₃ O ₁₂	7.13	0.964	8,	480	300	73	2.15	13%
(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

Fund Biolmag 2025

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

$$\text{e.g. NaI}(140\text{keV})=40 \cdot 140$$

$$=5600 \text{ photons at } \lambda \approx 400\text{nm}$$

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

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

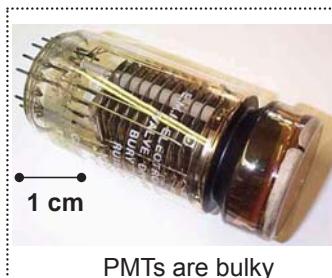
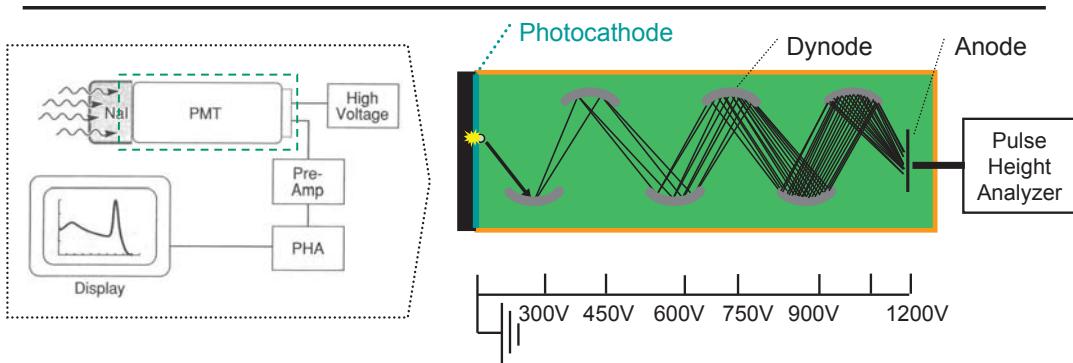
$<20\text{keV}$

} or $<120\text{eV/keV}$

5-13

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

Photomultiplier tube (PMT) -Noiseless amplification



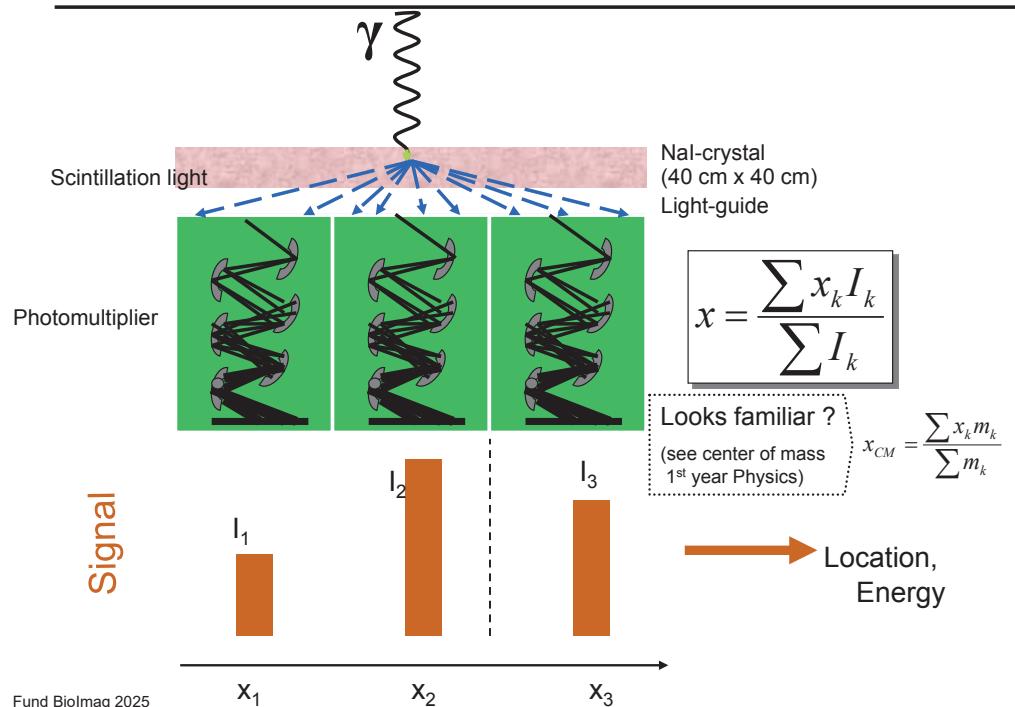
How to increase resolution beyond PMT dimensions ?

5-14

Fund Biolmag 2025

How to improve the spatial resolution of PMT ?

(Anger, 1964)

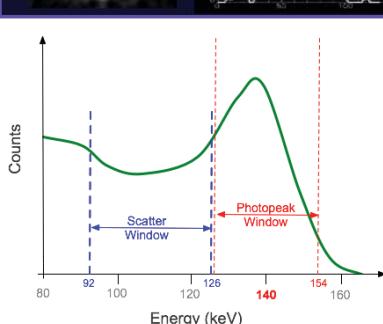
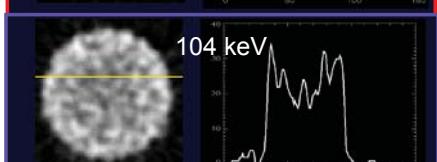
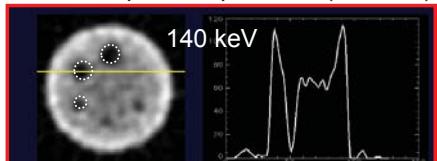


Fund Biolmag 2025

5-15

5-6. How to discriminate scattered photons ?

Tc-99m spherical phantom (w. holes)

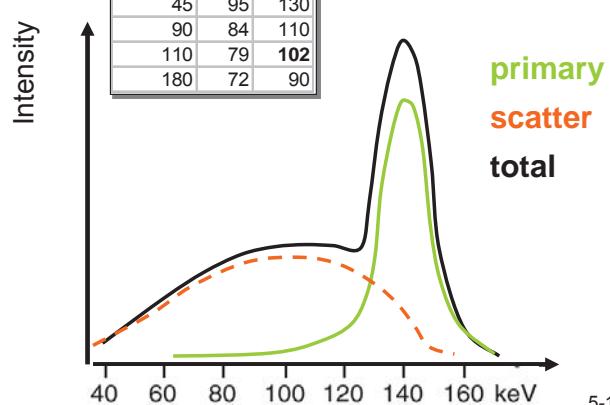


Most scattering is by Compton

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

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



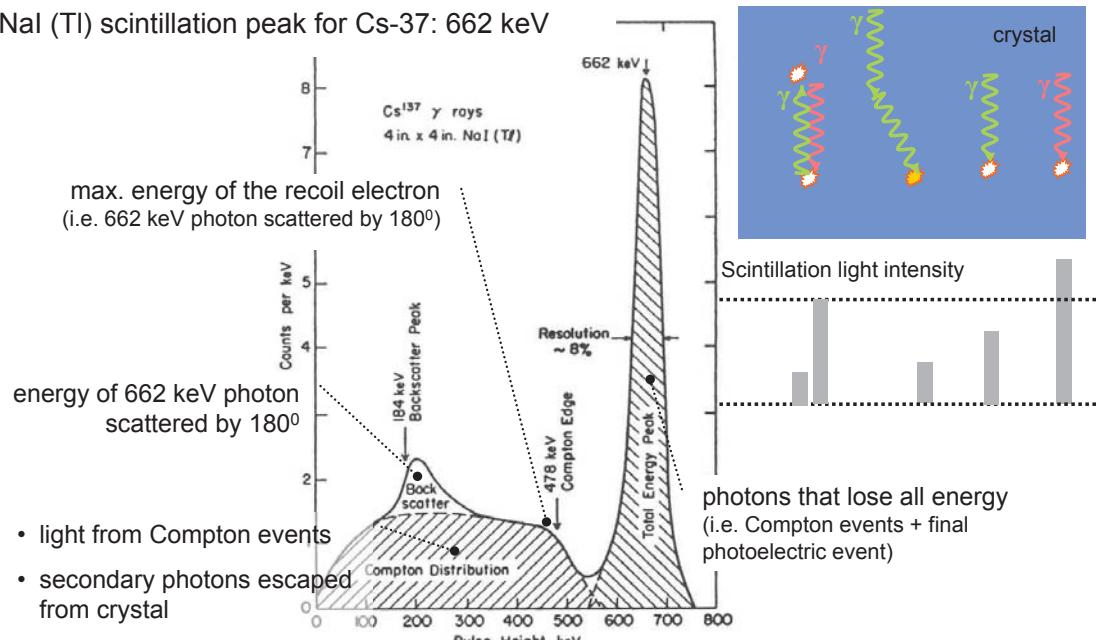
Fund Biolmag 2025

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



5-17

Fund Biolmag 2025

SPECT summary

Single Photon Emission Computed Tomography

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

5-18

Fund Biolmag 2025