# 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 ?

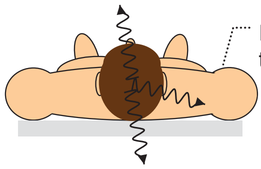
After this course you
1. Understand the reason for collimation in imaging γ-emitting tracers and its implication on resolution/sensitivity
2. Understand the implications of x-ray absorption on emission tomography
3. Understand the basic principle of radiation measurement using scintillation
4. Are familiar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



# 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**)

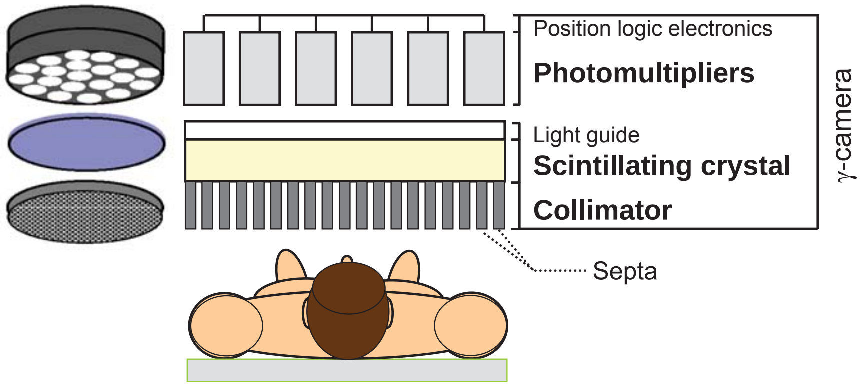
**-> Emission** computed tomography

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 |

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





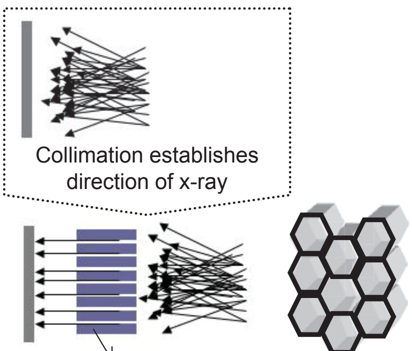


## 5-2. How can directionality of x-rays be established ?

Collimation

**Problem:** Photon detection alone does not give directionality

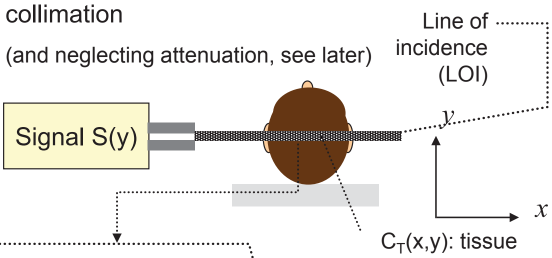
**Solution:**




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

Consider one detector, assuming perfect collimation

(and neglecting attenuation, see later)

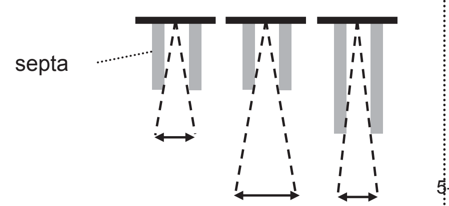



$$S(y)=\int_{\infty}^{-\infty} C_T(x,y)\,dx$$

Radon transform

⇒ Reconstruction as in CT

Impact of collimation on resolution



# How does collimation affect resolution ?

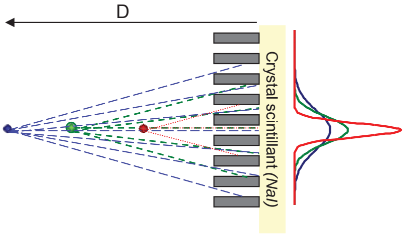
It's never perfect …

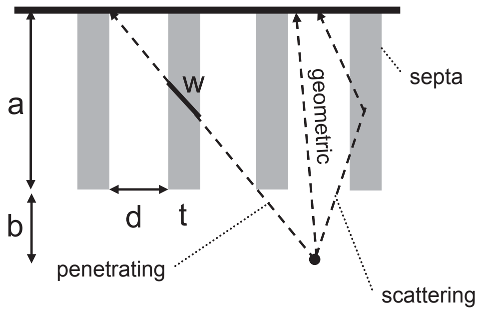
Perfect collimation, i.e. resolution ?

$d/a \rightarrow 0$

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

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 !**

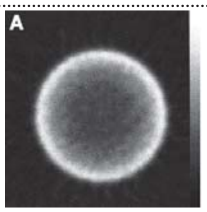




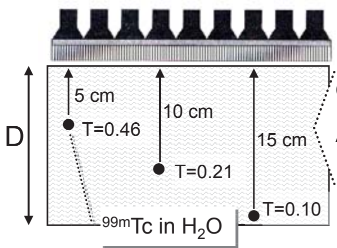
# 5-3. How to deal with attenuation of the emitted x-rays ?

result of x-ray absorption in tissue

Signal measured from a homogeneous sphere ($C_T(x,y)$=constant)




Intensity distortion:
Cause ?




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

Consider point source:

Attenuation depends on location of source in tissue

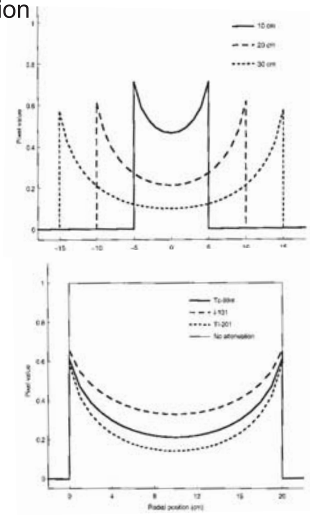
$$\mu_{water}(140keV) = 0.16\,cm^{-1}$$

$\rightarrow \mathrm{HVL} = 0.693/\mu \cong 4.5\,\mathrm{cm}$

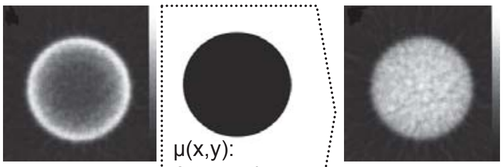
Attenuation T $\quad T = \frac{n(D)}{N_0} = e^{-\mu D}$

1. depends on object dimension and source location (D=f(object))

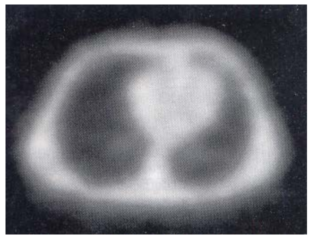
2. Photon energy $\mu = f(E_\gamma)$



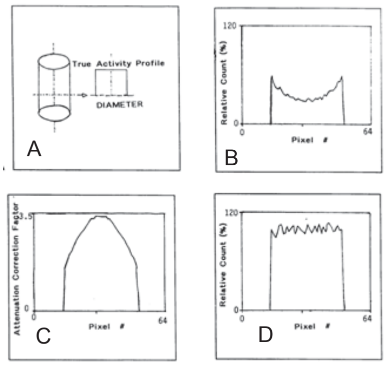
## What are the basic steps in attenuation correction ?



Measured | μ(x,y): Attenuation correction | Corrected image



A(x,y) of thorax




**Attenuation correction procedure**

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

Problem is prior knowledge needed for A (i.e. μ(x,y))

Attenuation correction rarely applied!



## How to simplify attenuation correction ?

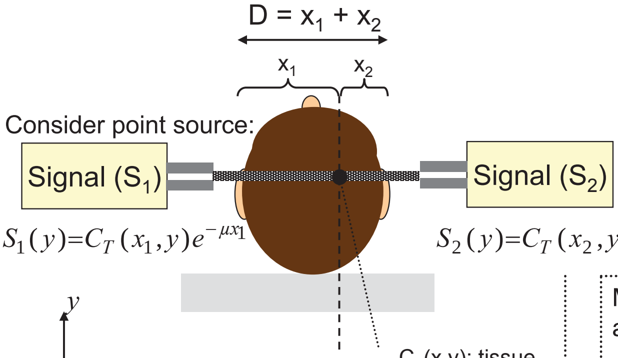
by measuring at $180^0$ using geometric mean

**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)

Consider point source:




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

$C_T(x,y)$: tissue radioactivity

Measure at $180^0$ simultaneously and take the geometric mean

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

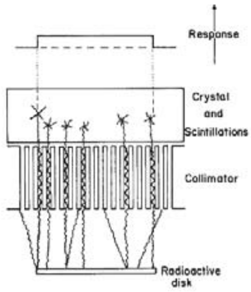
**Solution:** Geometric mean of the two $180^0$ opposite signals:

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

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

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

Collimation, followed by scintillation and amplification




Scintillator crystal e.g. Tl-doped SodiumIodide (NaI)

Photomultiplier Tube


Light electrons El. Signal

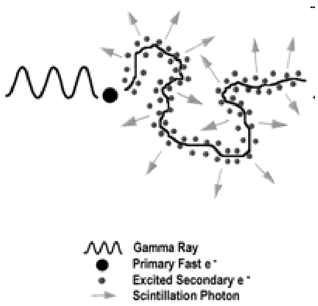
**γ-energy ∝ # scintillation photons ∝ Signal**

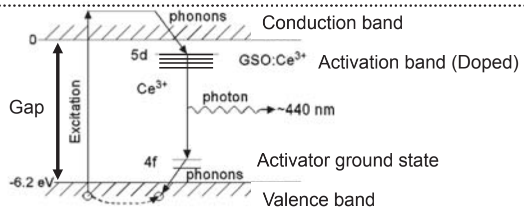


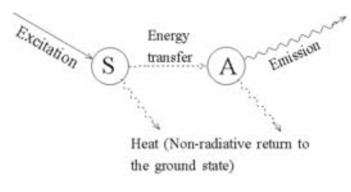
# What is Scintillation ?

**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)




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 | ~$10^4$ | | | |
| $Bi_4Ge_3O_{12}$ | 7.13 | 0.964 | 8, | 480 | 300 | 73 | 2.15 | 13% |
| $(Y,Gd)_2O_3$:Eu,Pr | 5.9 | 0.503 - 0.637 | 19 | 610 | ~$10^6$ | | | |
| $Gd_2O_2S$:Pr,Ce,F | 7.34 | 0.786 | 40 | 510 | ~$10^3$ | | | |
| NaI:Tl | 3.67 | 0.343 | 40 | 415 | 230 | 51 | 1.85 | 100% |
| $Gd_2SiO_5$:Ce | 6.71 | 0.704 | 7, | 430 | 300 | 59 | | |
| $Lu_2SiO_5$: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 λ≅400nm

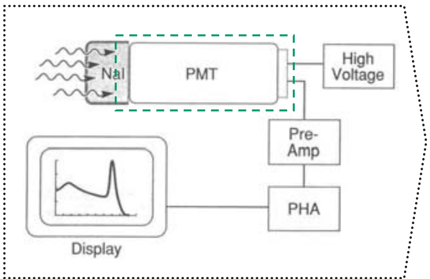
$E_{400nm}$[keV]=hc/λ = 1.2/λ [nm] =1.2/400 keV=3eV

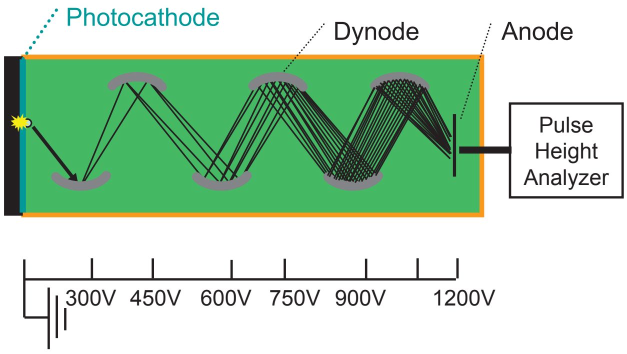
<20keV or <120eV/keV



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

Photomultiplier tube (PMT) -Noiseless amplification





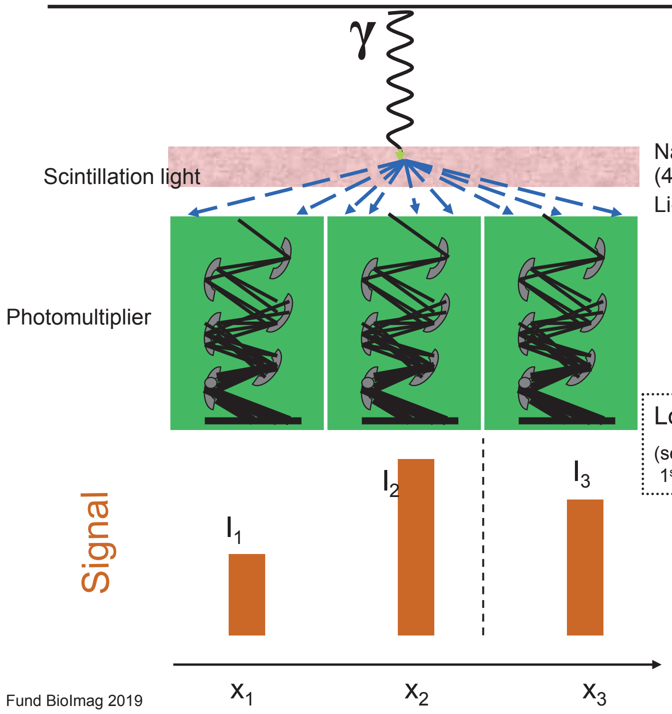
PMTs are bulky

Scintillator crystal

How to increase resolution beyond PMT dimensions ?

# How to improve the spatial resolution of PMT ?

(Anger, 1964)




$$x = \frac{\sum x_k I_k}{\sum I_k}$$

Looks familiar ?

(see center of mass 1st year Physics)

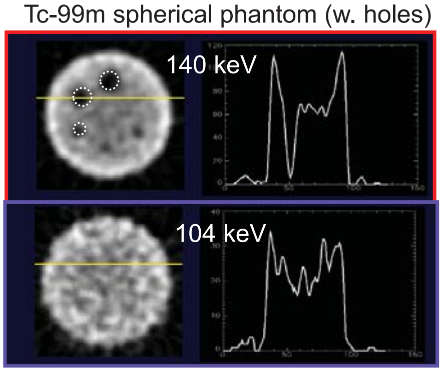
$$x_{CM} = \frac{\sum x_k m_k}{\sum m_k}$$

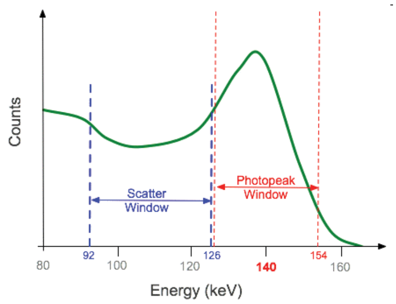
→ Location, Energy



# 5-6. How to discriminate scattered photons ?

Tc-99m spherical phantom (w. holes)



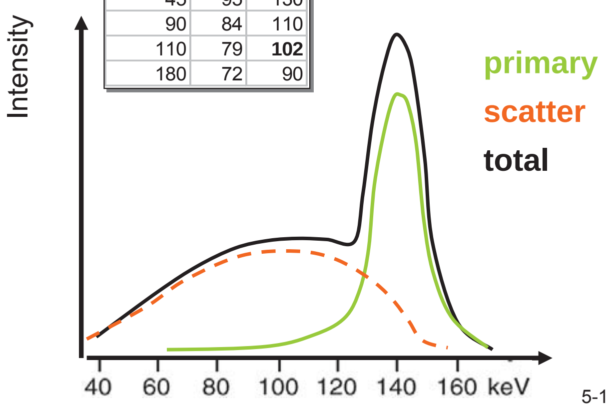




Most scattering is by Compton

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

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 |



## What processes contribute to the Scintillation light spectrum ?

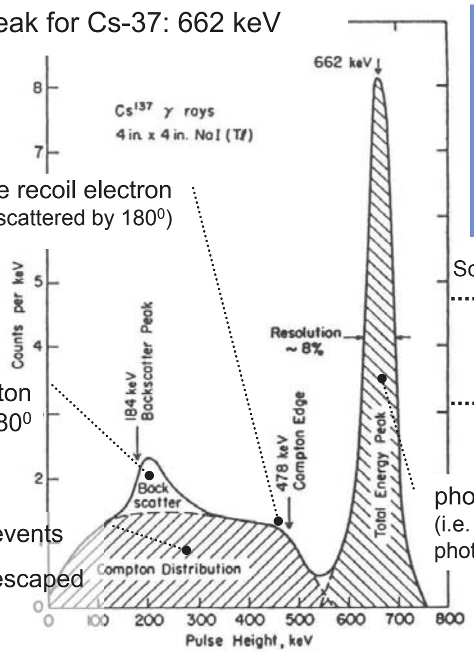
scintillation signal depends on x-ray energy

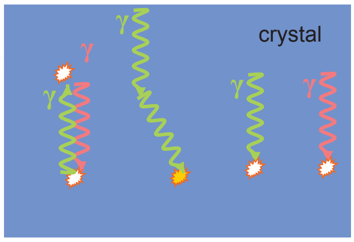
NaI (Tl) scintillation peak for Cs-37: 662 keV

max. energy of the recoil electron
(i.e. 662 keV photon scattered by $180^0$)

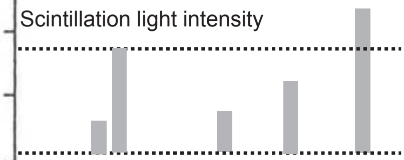
energy of 662 keV photon scattered by $180^0$

- light from Compton events
- secondary photons escaped from crystal




Scintillation light intensity



photons that lose all energy
(i.e. Compton events + final photoelectric event)



# SPECT summary

**S**ingle **P**hoton **E**mission **C**omputed **T**omography

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