MPHY0032 – Ionising Radiation Physics

Lecture 1 – Ionising Radiation

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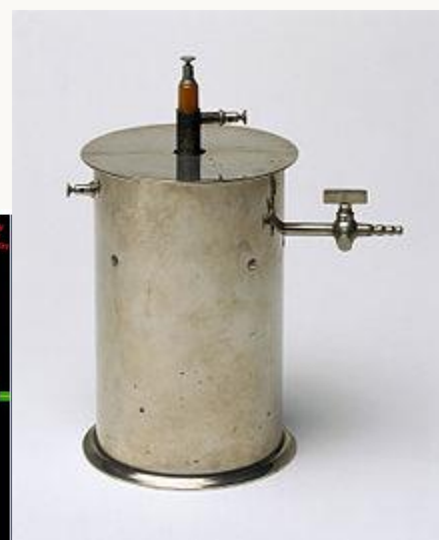
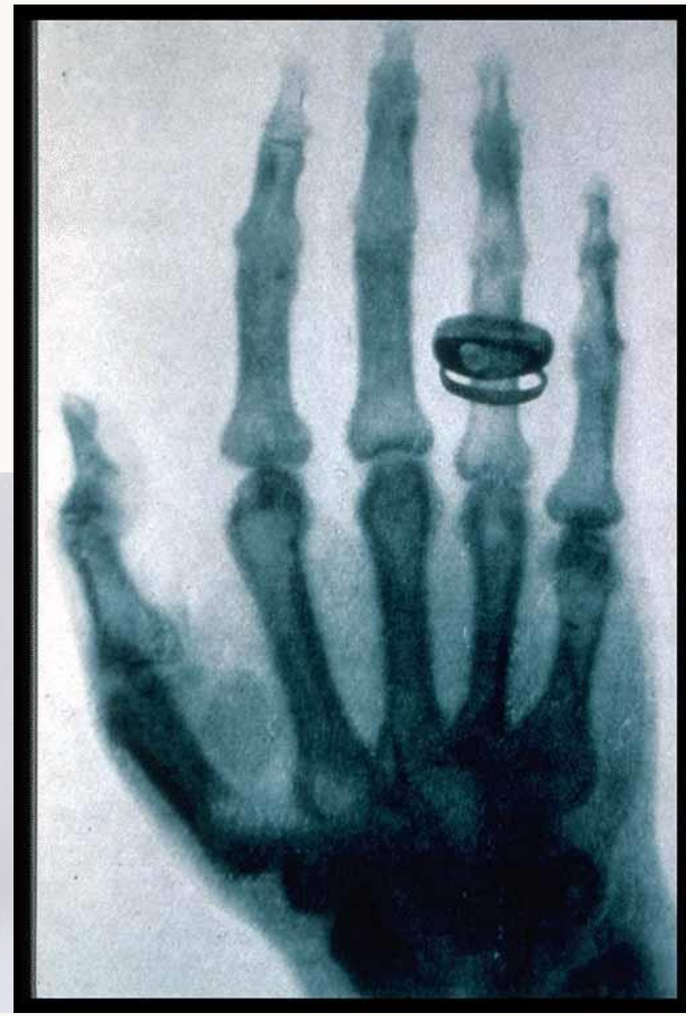
What is Ionising Radiation?

Why is it so important?



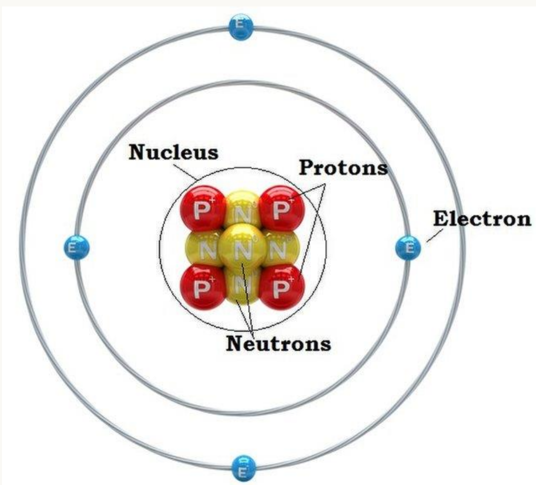


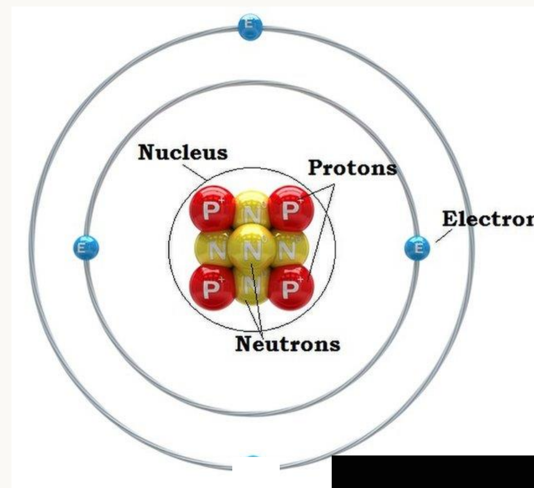
Ionising Radiation

Generally

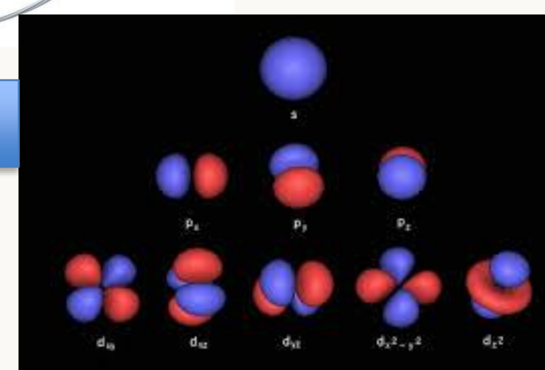
- Radiation carrying enough energy to free electrons from their atoms – making ions

Which is the Ion?





- How much energy is needed?
  - Enough to overcome the electron binding energy
    3.8 eV for Caesium lowest



Directly or Indirectly Ionising

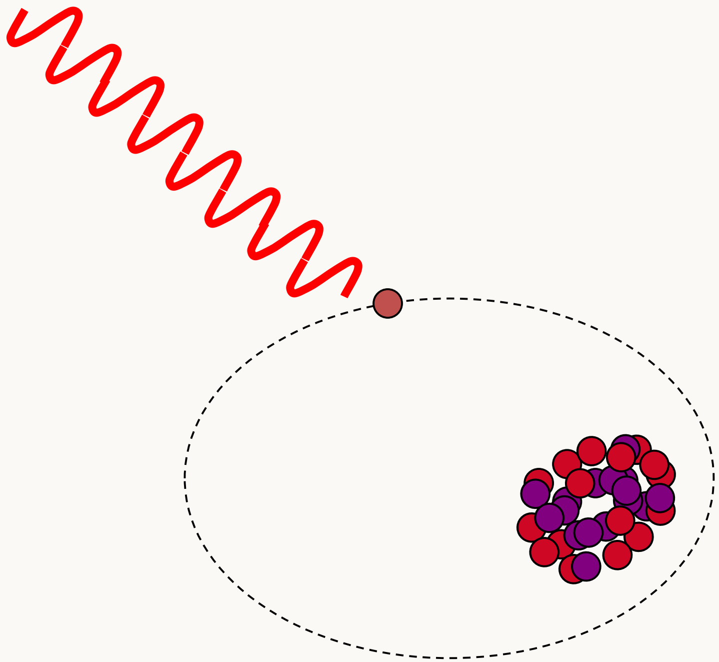
- Directly Ionising
  - Charged particles interacting directly via Coulomb's law to free atomic electrons
  - E.g. Alpha, Electrons, Protons

- Indirectly Ionising
  - Electrically neutral particles interacting to free electrons in secondary processes
  - E.g. Neutrons, Photons

- Only describes what happens to the targets
- In Medical Radiation Physics we can be interested in both what happens at the target and to the incoming particle

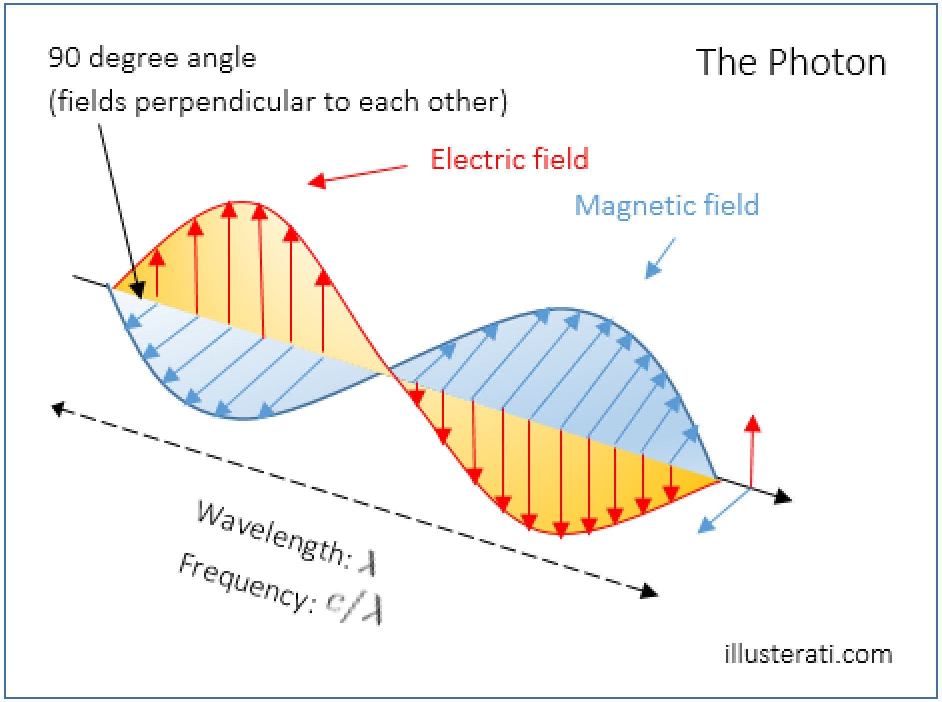
Radiation Interactions Relevant for Medicine

- Different interactions are useful for different areas
- Radiotherapy
  - Absorption is good - energy is delivered where the interaction occurs
  - Scatter is bad - blurs out the volume receiving dose
  - Transmission delivers no dose
- Imaging
  - Transmission and absorption are good for distinguishing different structures in the body
  - Too much absorption will give patient an unnecessary dose
  - Scattering blurs the image
  - Scattering is also why all the shielding is required



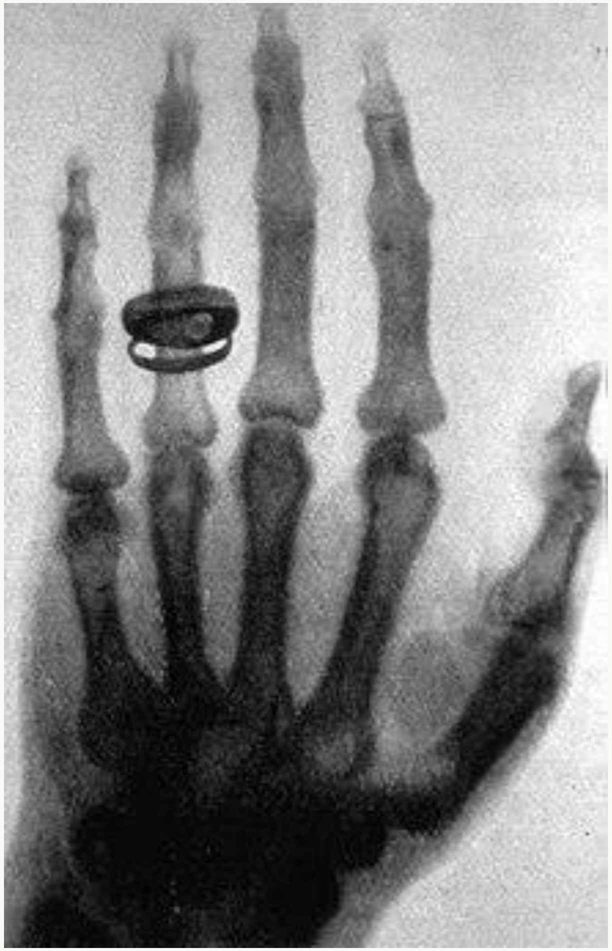
1. Photon Interactions

a) Attenuation quantities

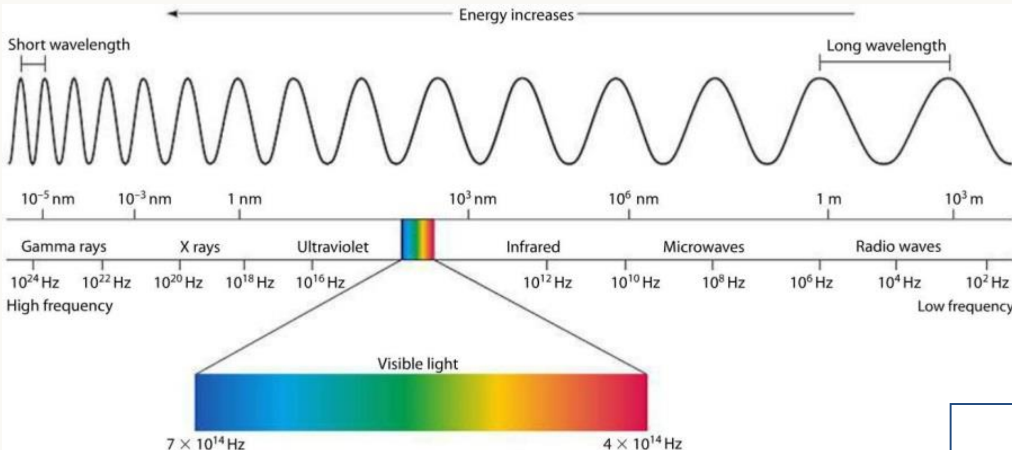


We'll look at charged particles and neutrons later this term

Why knowing about interactions is important



Photon energy - basics



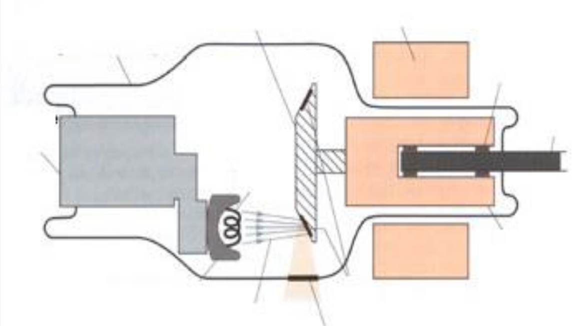
10^{-12}	pico	p
10^{-9}	nano	n
10^{-6}	micro	µ
10^{-3}	milli	m
10^{3}	kilo	k
10^{6}	mega	M
10^{9}	giga	G
10^{12}	tera	T
10^{-2}	centi	c

$$f = \frac{c}{\lambda}$$

$$E = h.f \quad (or\ E = h.\nu)$$

- X-rays
  - Part of the electromagnetic spectrum,
  - Sub nanometer wavelength
  - High frequency, therefore high photon energy
- Electron Volt (eV)
  - Unit of energy required to move an electron through an electrical potential of one volt

$$E = q.V$$



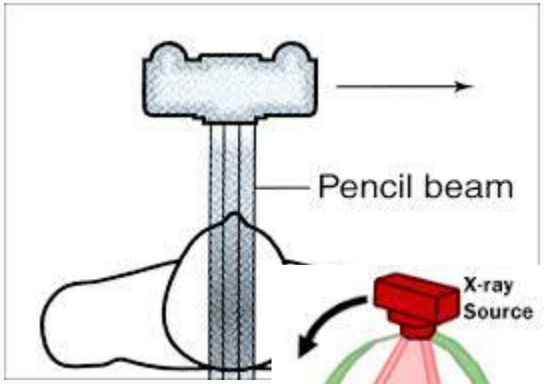
Terms to describe radiation - 1

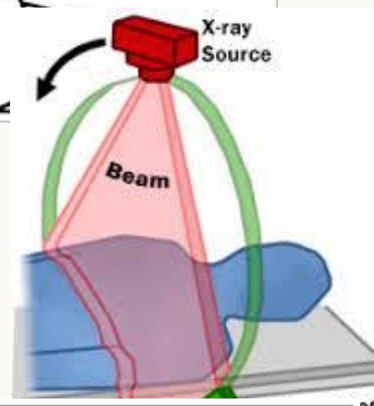
- Number, N
  - Numbers of photons incident on tissue
- Fluence, ϕ
  - Number of photons incident on a particular area of tissue
- Energy fluence, ψ
  - The energy of photons passing through a particular area of tissue
- Intensity, I
  - The energy fluence rate – the energy passing through a particular area of tissue in a particular time

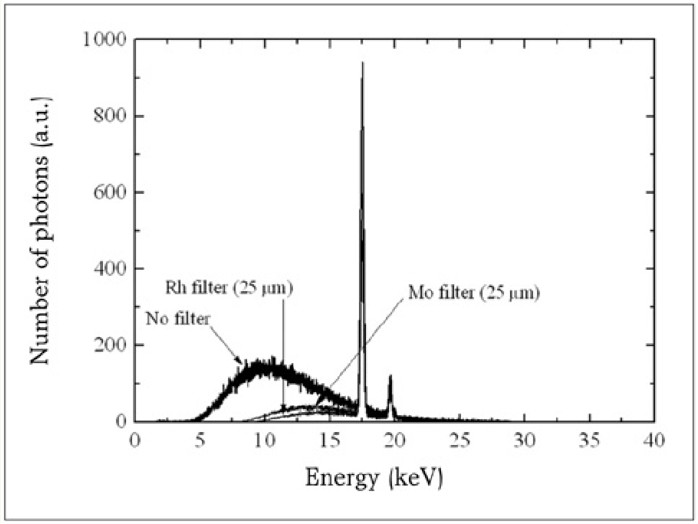
Terms to describe radiation - 2

- Narrow (beam geometry)
  - beam is thin and collimated like a pencil lead
- Broad (beam geometry)
  - beam is wide, often in a fan shape radiating outward
- Mono (energetic)
  - beam is made up of photons with a single energy (or a small range)
- Poly (energetic)
  - beam is made up of photons with many different energies (over a wide range)

- Take care to avoid confusion and if in doubt, read the book / question carefully!

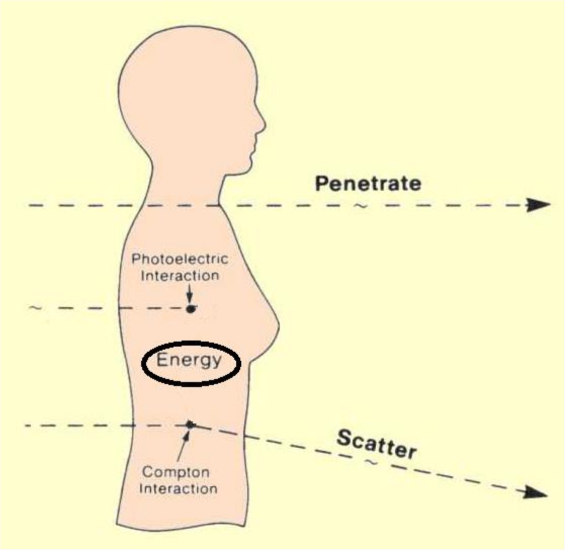


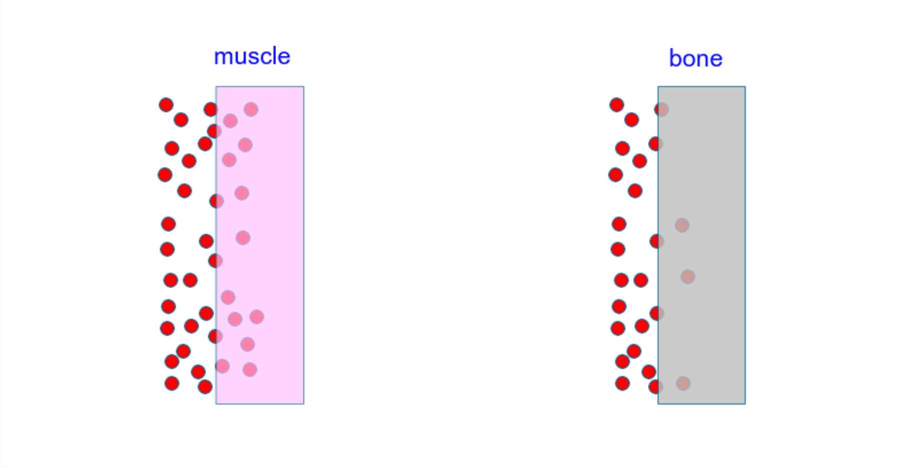




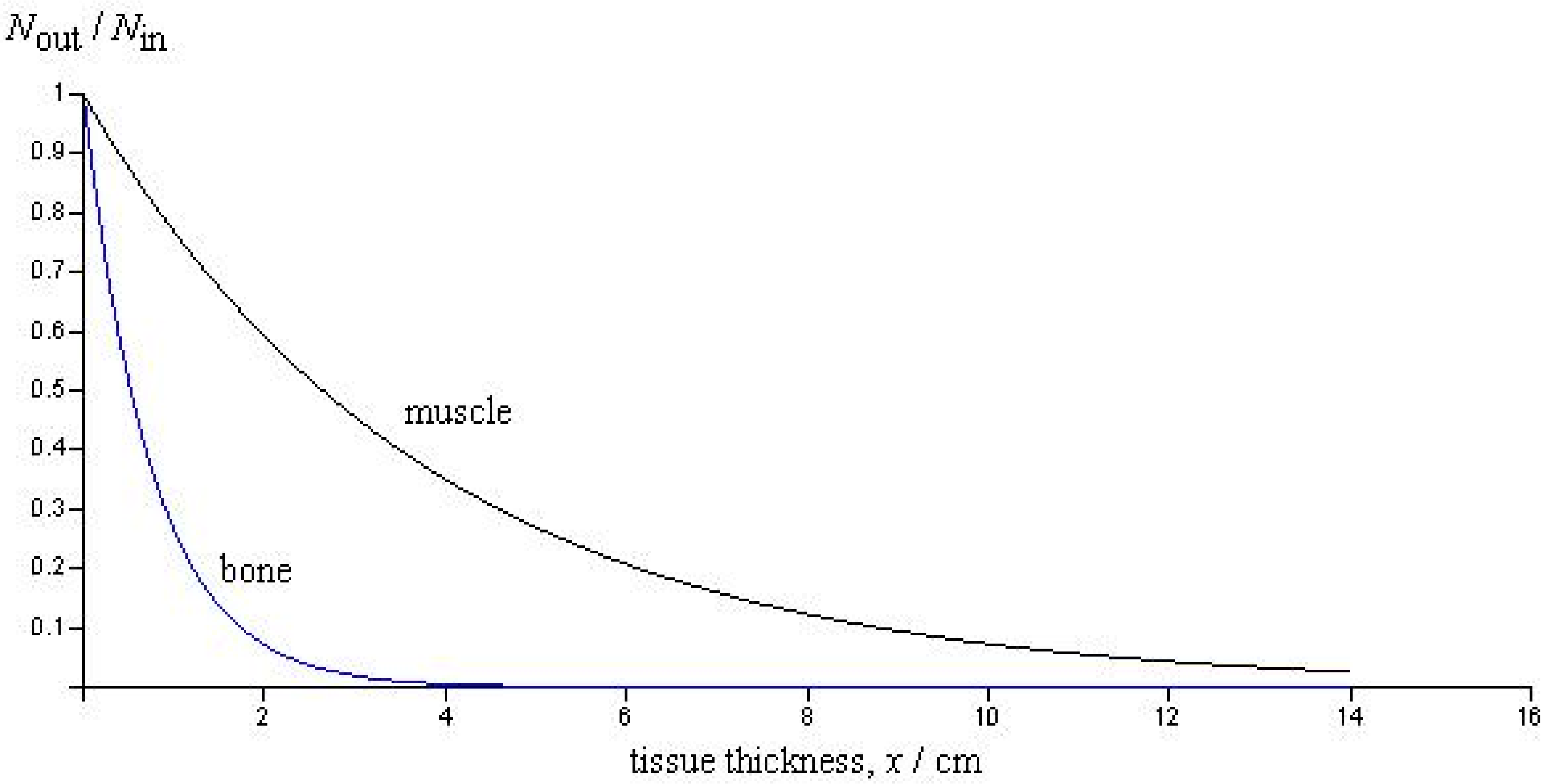
Interactions of photons with matter

- Transmission
- Absorption
- Scatter
- Which happens depends on
  - Photon energy
  - Target matter
  - Luck



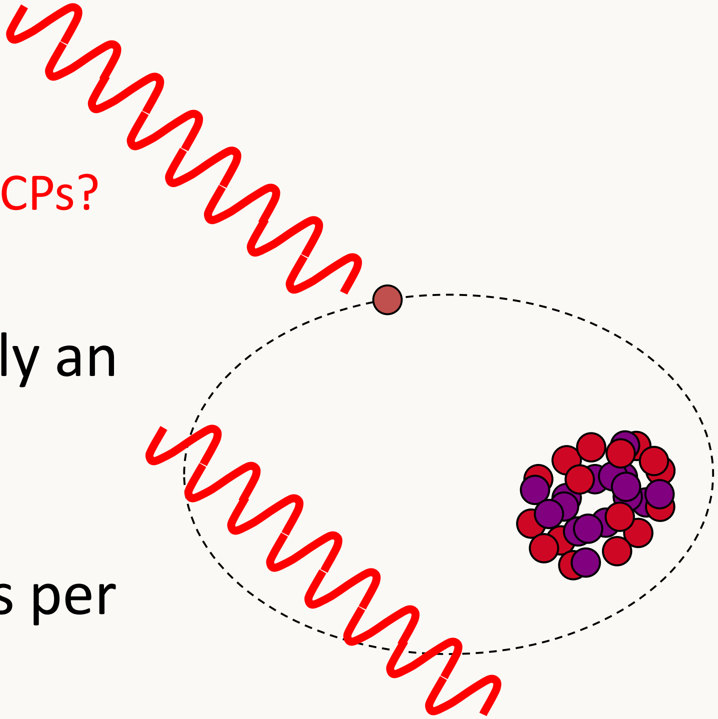


Extent of Penetration



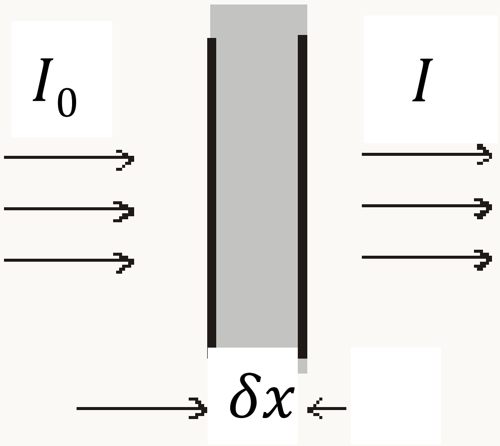
Photon Interactions are probabilistic

- Generally interact with electrons in atoms
- Some may pass and not interact
  - Why more possible when compared to CPs?
- The thicker the tissue, the more likely an encounter with an atomic electron
- Some materials have more electrons per atom
  - More likely to interact



Attenuation (narrow, mono)

- The reduction of intensity of a beam of photons as it passes through a thickness of tissue (x)
  - Caused by absorption / scattering

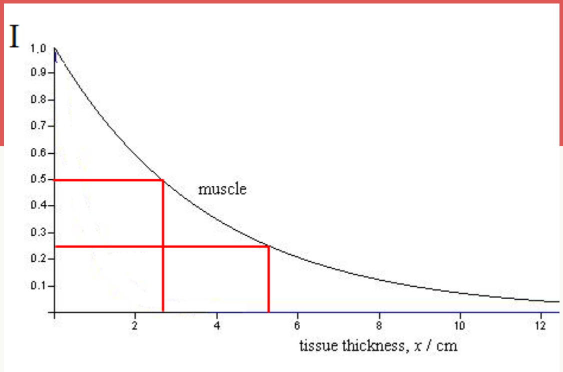


$dI = Intensity\ lost\ in\ \delta x$

  - Experimentally shown that the percentage reduction depends exclusively on the thickness x
  - Successive layers of material thickness x will attenuate the same fraction each time

Attenuation equation

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



- Intensity decreases with further distance into the tissue (as more atoms interact with the photons).

- Total linear attenuation coefficient, μ
  - A measure of likelihood of photon being attenuated within a given length
  - Units of mm^{-1} or cm^{-1} – CAREFUL WITH CONVERTING BETWEEN!
  - Varies with material type (different density and atomic number Z)
  - Varies with photon energy – generally **higher Energy means lower μ**

- Mean free path
  - Equal to 1/μ
  - Average distance travelled by a photon before interacting
  - Expect a reduction to 37% of original at this depth
  - Useful for eyeball calculations

Moodle Quiz – Radiation Interactions

Attempt Qs 1-3

Attenuation coefficient constituents

- μ measures total attenuation by measuring the intensity of beam before and after the material
- Each interaction mechanism (scatter/absorption) will have a different likelihood of occurring at a given photon energy
- Therefore μ of is made up of constituent parts:
  - τ (tau) – Linear attenuation coefficient for photoelectric effect
  - σ (sigma) – Linear attenuation coefficient for Compton effect
  - κ (kappa) – Linear attenuation coefficient for pair production

Learn about these soon

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

Mass attenuation coefficients

- Each of the interaction mechanisms depends strongly on the density of the material
  - Unlikely to change much for most solids, but can be very significant for gases

- To make the measurements of attenuation of each mechanism independent they are often given as mass-attenuation coefficients

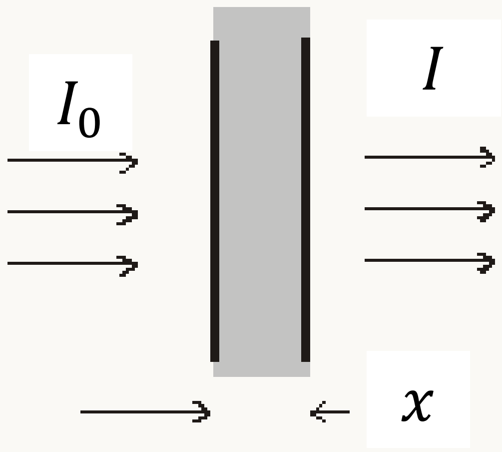
$$mass\ attenuation\ coeff = \frac{linear\ attenuation\ coeff}{density\ of\ material}$$

- Giving:
  - τ/ρ, σ/ρ and κ/ρ – they generally don't have their own symbol
  - Units – $cm^2\ g^{-1}$
  - To find the linear attenuation coeff. Multiply the mass-attenuation coefficient by the material density

Final attenuation equation

- Combining all gives:

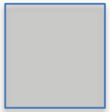
$$I = I_0 e^{-\left(\tau/\rho + \sigma/\rho + \kappa/\rho\right).\rho x}$$



I_0 = *Initial intensity*

I = *Final intensity*

x = *thickness of material*



Boxed to denote a single quantity

Example 1

1. What thickness of concrete and lead are needed to reduce the intensity of 500keV photons in a narrow beam to on quarter of its original?
2. Repeat for 1.5 MeV photons

TABLE 8.2 Mass Attenuation Coefficients

	μ/ρ (cm^2 g^{-1})	
$h\nu$	Concrete $\rho = 2.35$ g cm^{-3}	Pb $\rho = 11.4$ g cm^{-3}
500 keV	0.089	0.15
1.5 MeV	0.052	0.051

Example from Turner pg 189

UCL

Example 2

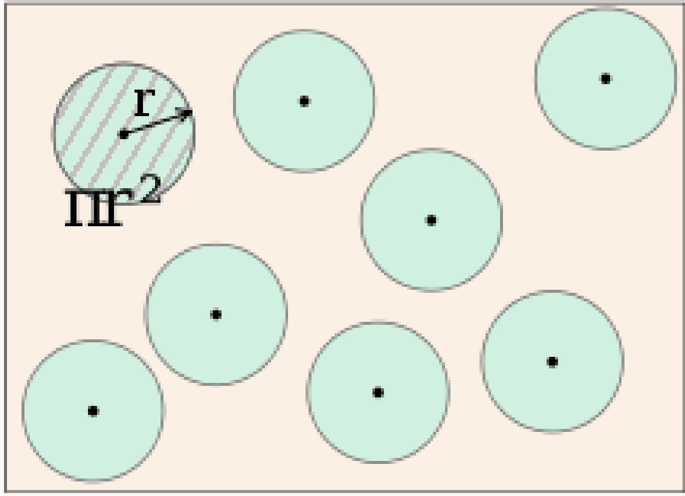
(c) A phantom (a representation of the patient used in X-ray experiments) is to be made to represent a compressed breast undergoing mammography. The phantom is to be made by placing a 1 cm thick slice of breast tissue on top of a block of Perspex so that the two materials together will behave as a 4 cm thick breast. Use the data given (graph paper is provided if required) to calculate the thickness of Perspex that should be used. Assume that the spectrum of a mammographic X-ray beam can be represented by a monoenergetic beam of 18 keV and that the physical density of breast and Perspex are 1.02 g cm^{-3} and 1.19 g cm^{-3} respectively. [7]

material	**8 keV**	**10 keV**	**15 keV**	**20 keV**	**30 keV**
$\mu/\rho_{\mathbf{breast}}$ [cm^2g^{-1}]	0.181	0.169	0.149	0.136	0.118
$\mu/\rho_{\mathbf{perspex}}$ [cm^2g^{-1}]	0.175	0.164	0.146	0.133	0.115

Interaction Cross sections

- Attenuation coefficients can be related further back to the specific atoms in a material
- Interaction cross section:
  - The probability of an interaction in a medium
  - The effective area an atom presents to a photon for a particular reaction
  - Larger areas mean greater chance of interaction
  - Rather confusingly given the symbol σ (sigma)
  - Useful when calculating attenuation through mixtures of atoms (i.e. tissue)
  - Common values in look-up tables

total area A



Units of cm^2 although the unit barn is common – $10^{-24} cm^2$

Calculations using interaction cross sections

$$\mu = N.\sigma$$

$N = Atom\ density\ (\#\ cm^{-3})$

$\sigma = Atomic\ cross\ section$

- Atom Density N, the number of atoms per unit volume

$$N = \frac{\rho N_A}{M_r}$$

$N_A = Avogadro's\ number$

$\rho = material\ density\ (g\ cm^{-3})$

$M_r = Relative\ atomic\ mass$

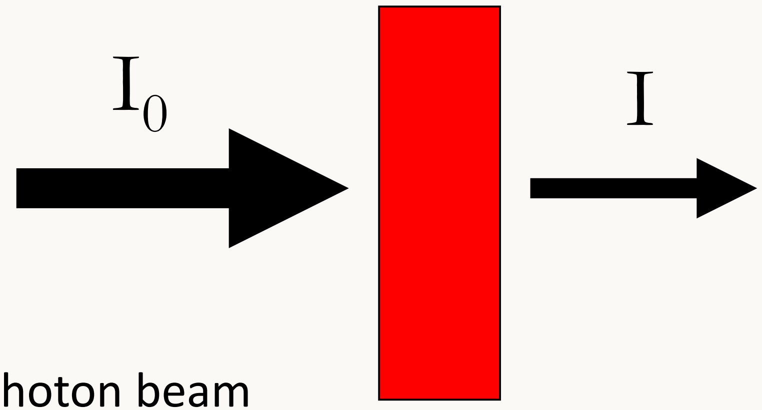
- Combining these equations gives the relationship between the linear attenuation coefficient and atomic cross section for photon interaction with any element
- For a compound or a mixture, the separate contributions from each element can be added to obtain μ

$$\mu_{total} = N_1\sigma_1 + N_2\sigma_2\ \ldots etc$$

Note – each interaction mechanism can have a separate cross section value

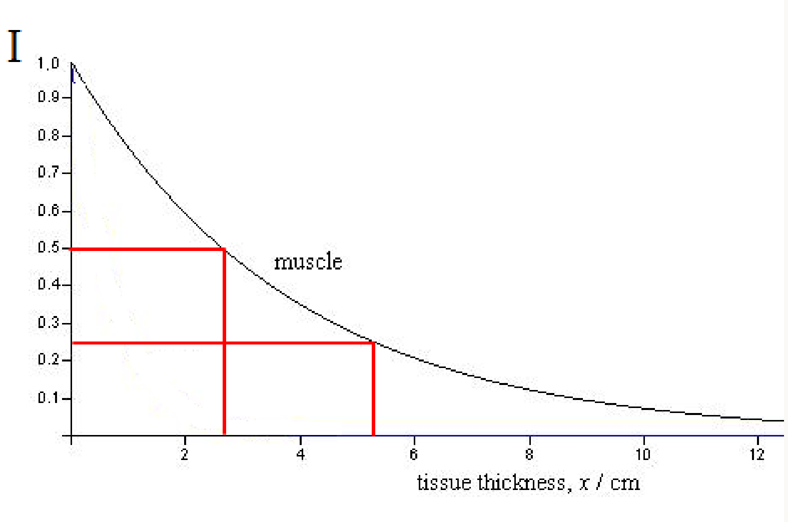
Summary of attenuation quantities

- Linear attenuation coeff, μ
  - Measure of total attenuation of a photon beam
  - Units – cm^{-1}
- Mass attenuation coeff, μ/ρ
  - Separates out density of material
  - Units – $cm^2\ g^{-1}$
- Interaction cross section, σ
  - Effective area presented to an incoming photon beam
  - Units – cm^2 or barns ($10^{-24}\ cm^2$)
- Each interaction mechanism can have it's own value of each
- All values change depending on energy of photon beam
  - You need to look up the values at the correct photon energy



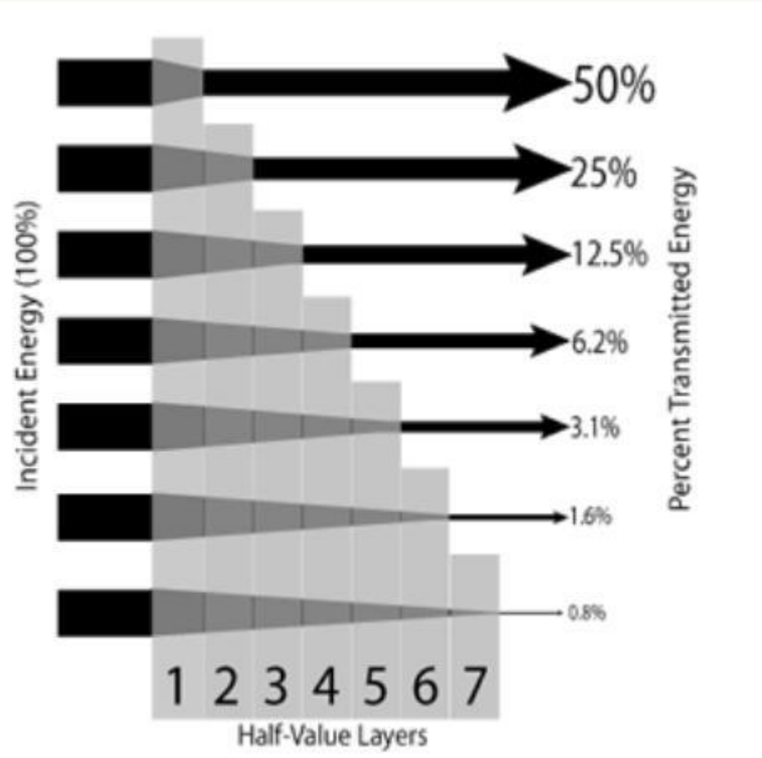
Half-Value Layer (HVL)

- The half-value layer is "the thickness of any given material where 50% of the incident energy (intensity) has been attenuated"

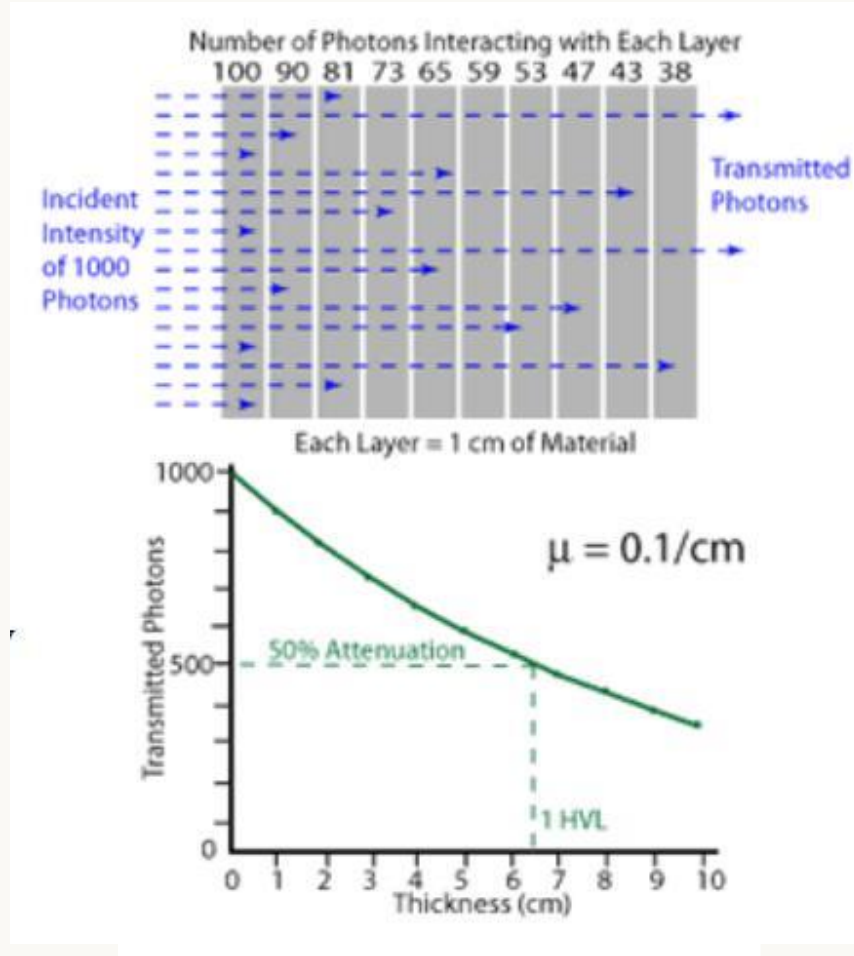


- Units of distance (i.e. mm or cm)
- Depends on the photon beam energy
- Increasing the energy of photons increase a material's HVL (higher energy photons are more penetrative)

Half-Value Layer



Number of half value layers	0	1	2	3	4
Intensity	I_0	$I_0/2$	$I_0/4$	$I_0/8$	$I_0/16$



HVL and μ

- HVL is inversely proportional to the linear attenuation coefficient, μ

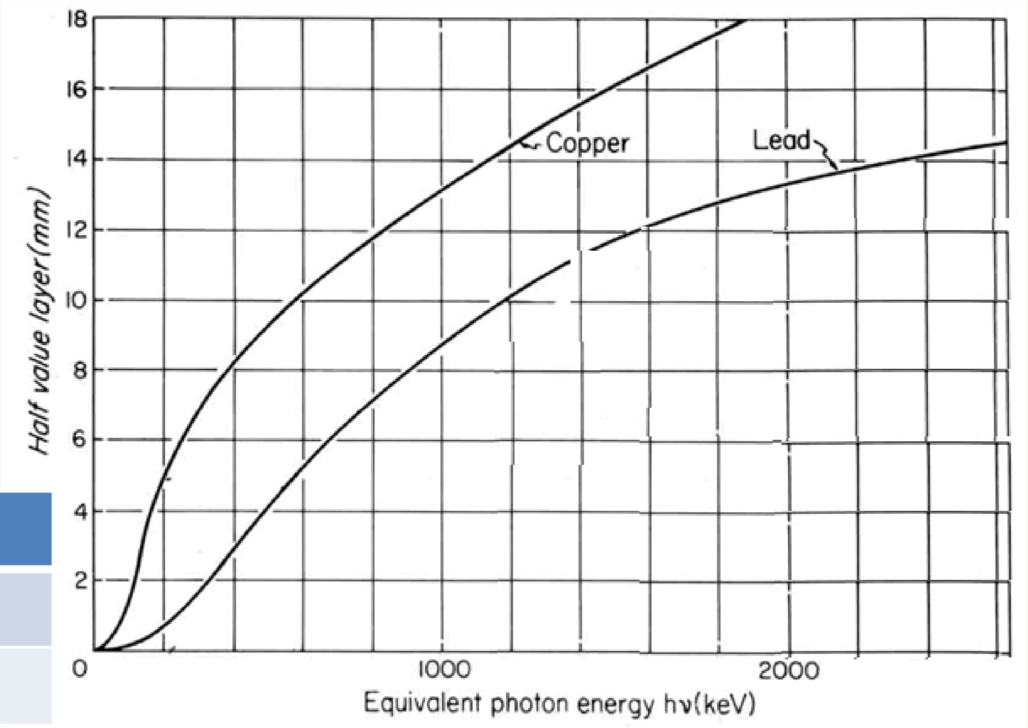
Who can derive the relationship?

HVL and μ

$$HVL = \frac{\ln 2}{\mu}$$

Units of HVL and μ must match

- Greater the photon energy the greater the HVL
- How would HVL relate to density of material?

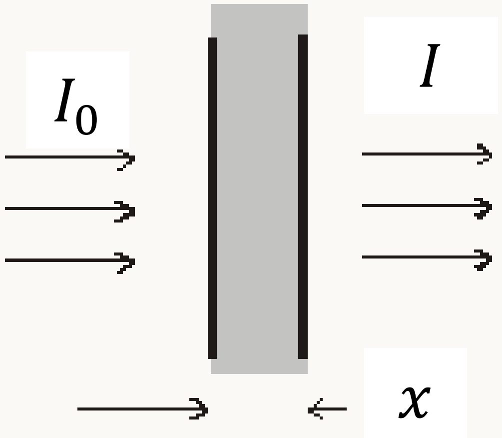


Photon Energy	Lead	Copper
1 MeV	8.5	13
2 MeV	13.5	19

QVL? TVL?

A common misconception with attenuation

- Confusing the energy of the beam with the energy of the photons within the beam
  - E.g. 10,000 photons with an energy of 20keV pass through a tissue (x)



  - A half-value layer does **not** lower the energy of the photons to 10keV (necessarily)
  - It reduces the number of photons to 5,000. The energy of the photons themselves can be changed, but still don't confuse with attenuation coefficients

i.e. $I = I_0 e^{-\mu . x} = 20000 e^{-\mu . x}$ is WRONG

Common misconceptions with attenuation

- When calculating, select μ based on the photon energy (20keV), not the beam energy.

- However…
  - The total energy in the beam is halved (neglect CS)
    - $10000 \times 20 \times 10^3$ - before attenuation
    - $5000 \times 20 \times 10^3$ - after attenuation

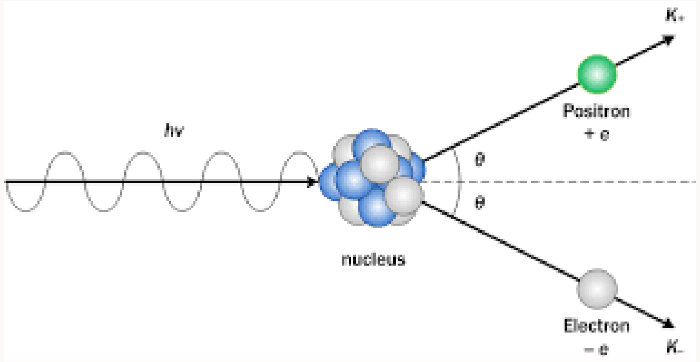
  - But the photons themselves are still each at 20keV

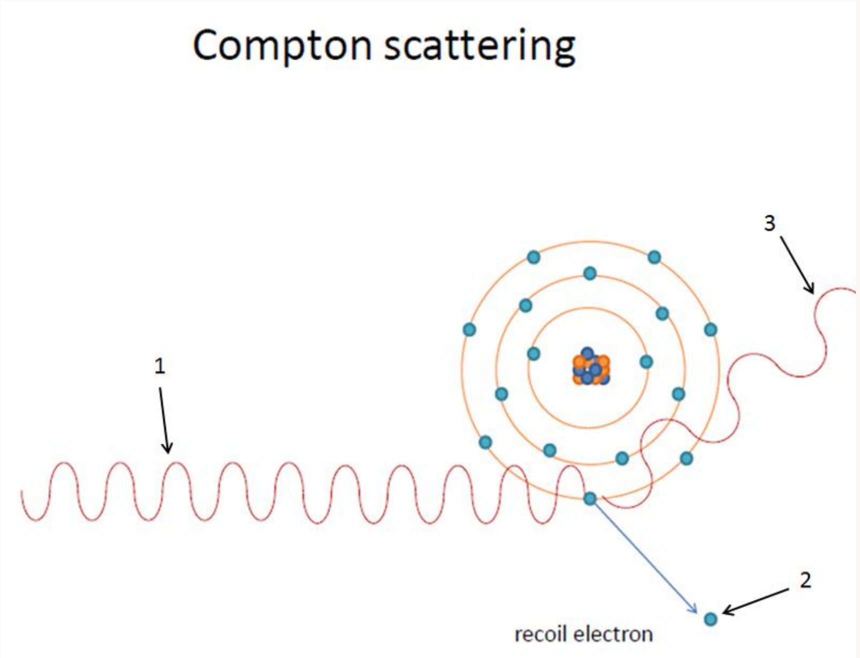
- So **Intensity** of the beam is halved
  - But the photons that make up the beam are still at 20keV

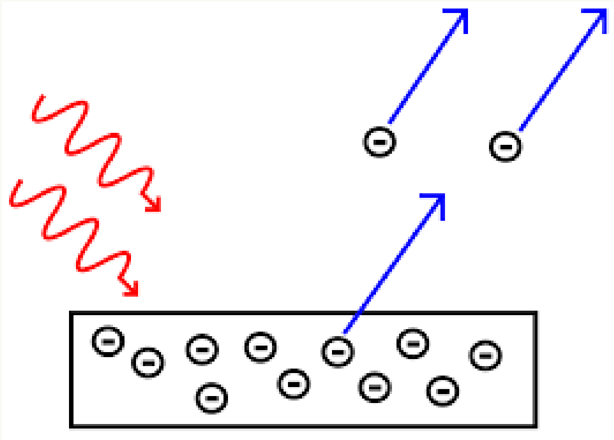
Next time

1. Photon Interactions

b) Interaction mechanisms







Any Questions?

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