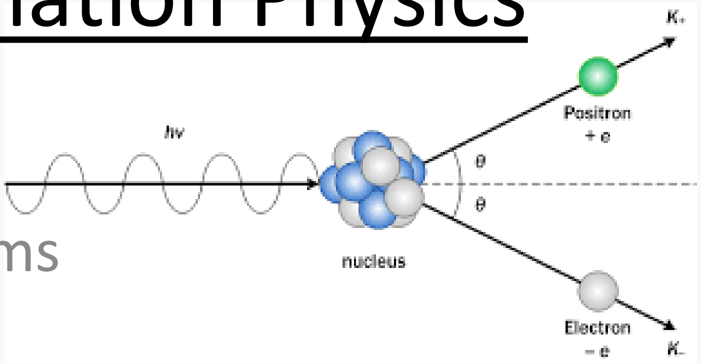
MPHY0032 – Ionising Radiation Physics



Lecture 2 – Photon Interaction mechanisms

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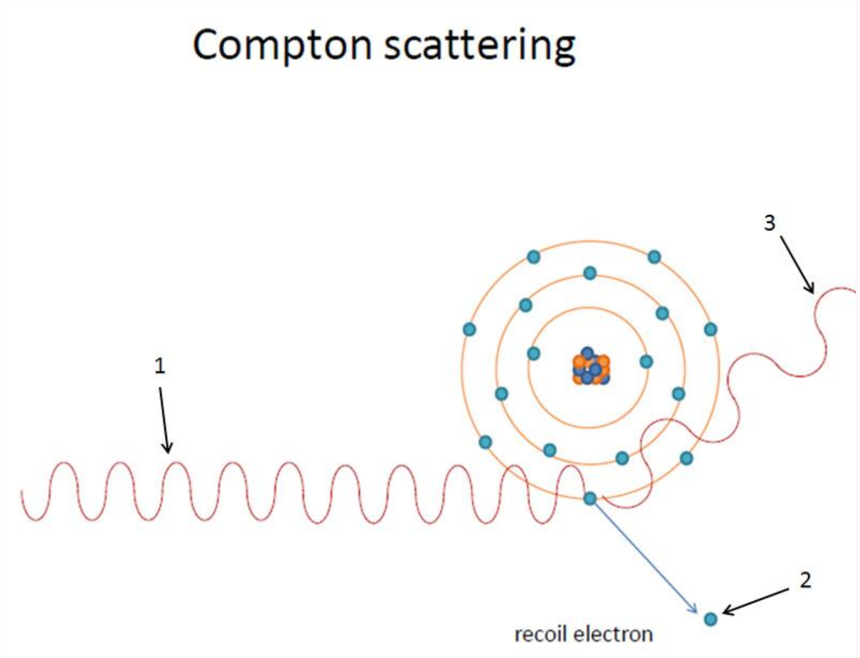
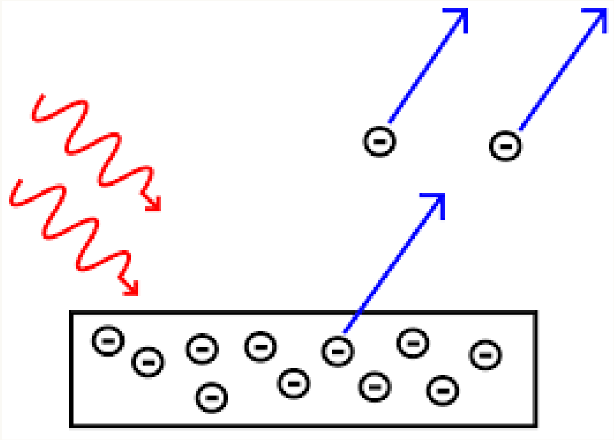
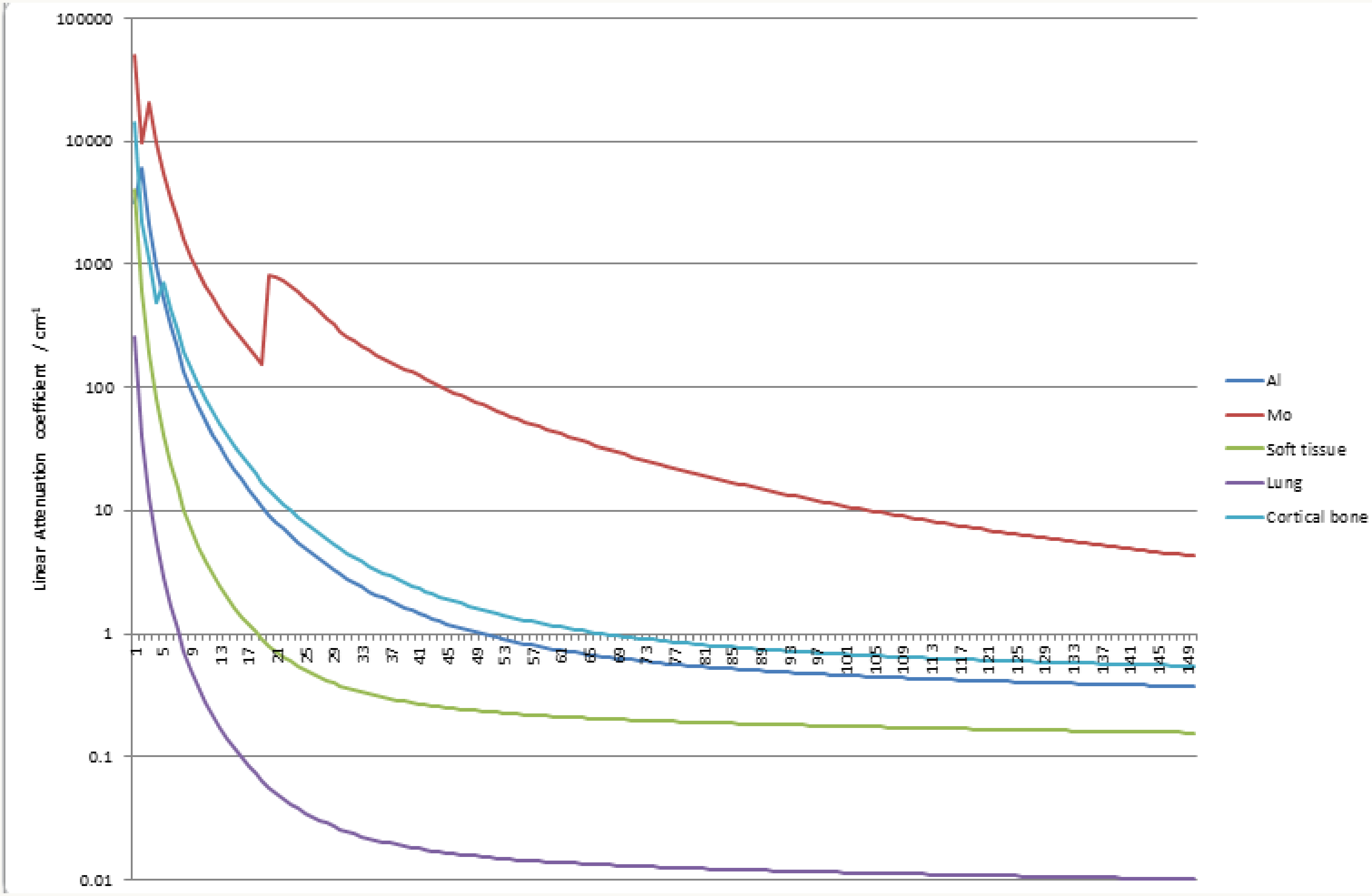




Review of last lecture

- Photon attenuation
  - Coefficients
    - probability of a photon being removed from beam by an interaction
    - Each mechanism can have it's own value
    - Mass attenuation (removes density effects)
  - Interaction cross sections
    - Effective area presented by one atom to incoming photons
    - Relates only to particular atom and photon energy
- Half-Value layer
  - Thickness of material to half the beam intensity
  - Varies with the material and incoming photon energy

Attenuation and HVL layer exercise



Points of interest from Exercise

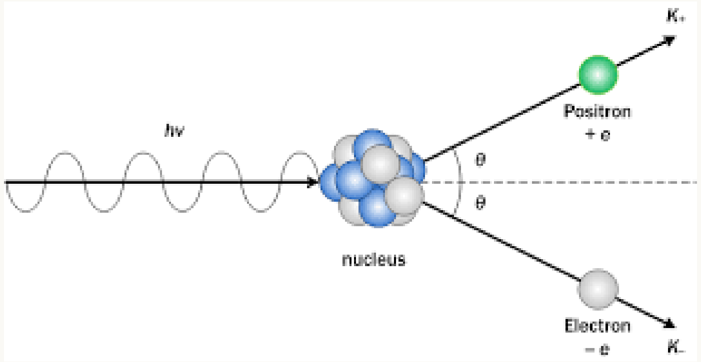
- Mass attenuation coeffs and linear attenuation coeffs can be quite different for the same material
- Generally, the higher the photon energy the more penetrating the radiation
- Broad beams can produce significant differences from narrow beams
- HVL calculations for a polyenergetic beams might not be trivial (although you can approximate using effective energy)

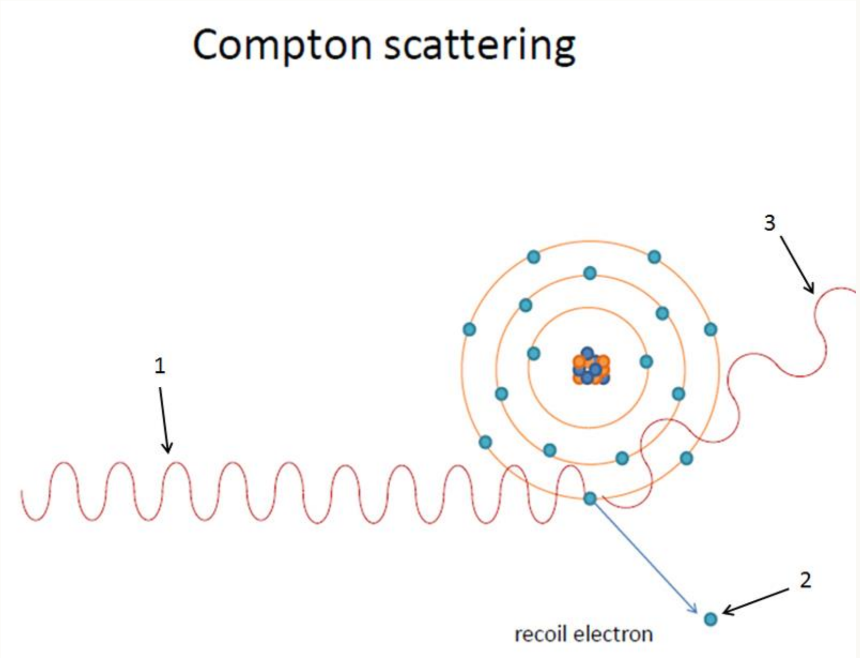
■ DETERMINATION OF EFFECTIVE ENERGY

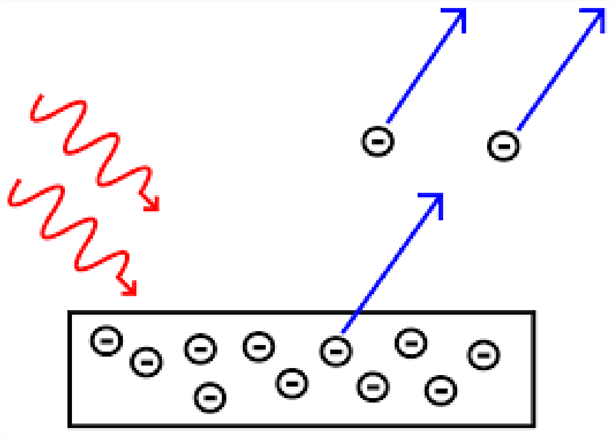
For polychromatic x-ray beams (which contain a spectrum of photon energies), the penetration and thus the HVL is different for each energy. The effective energy of an x-ray beam is the energy of a monoenergetic beam of photons that is attenuated at the same rate as the x-ray beam, in other words, that has the same HVL as the spectrum of photons in the beam. The effective energy is about 30%–50% of peak energy.

1. Photon Interactions

b) Interaction mechanisms

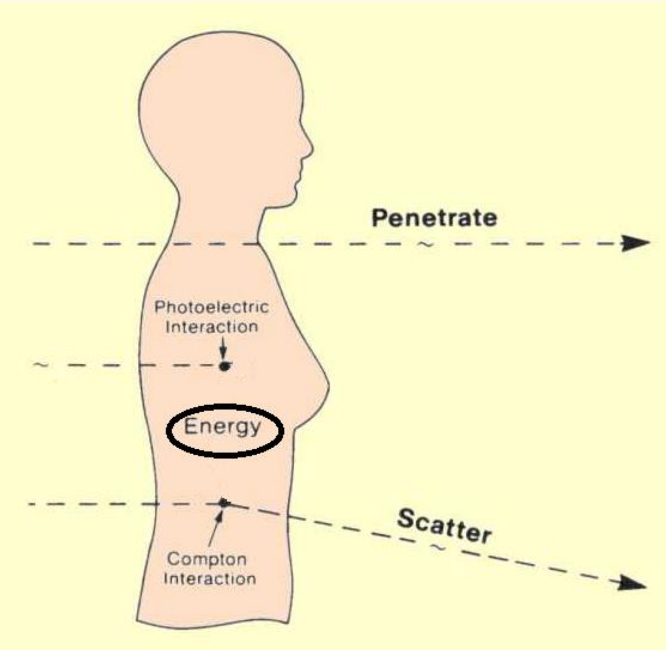


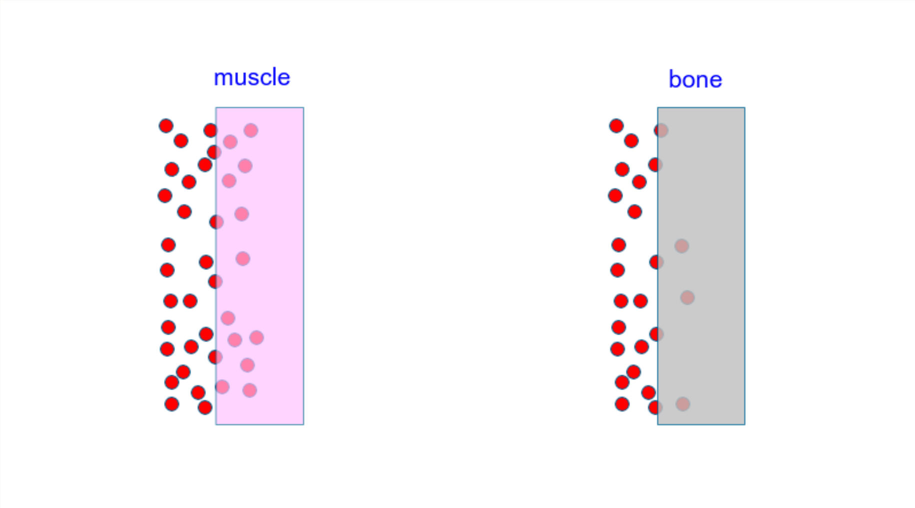




Interactions of photons with matter

- Transmission
- Absorption
  - Photoelectric effect
  - Pair production
- Scatter
  - Thompson, Rayleigh
  - Compton
- Which happens depends on
  - Photon energy
  - Target material
  - Luck

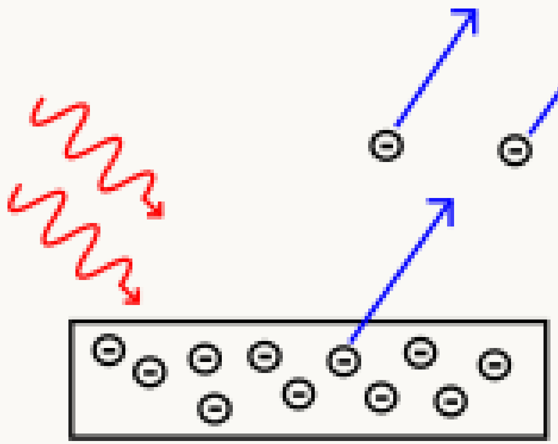




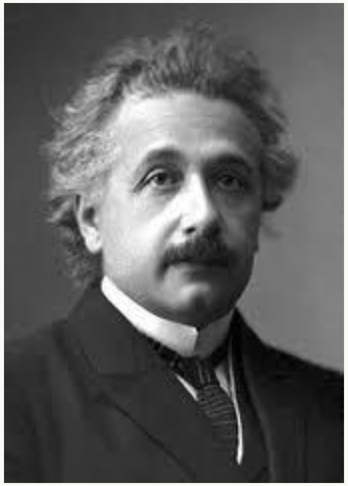
i) Photoelectric effect (absorption)

- Experiment results and theory to explain it of great significance to the physics world
  - Showed the particular nature of light

- Light goes in, electrons come out



Albert Einstein

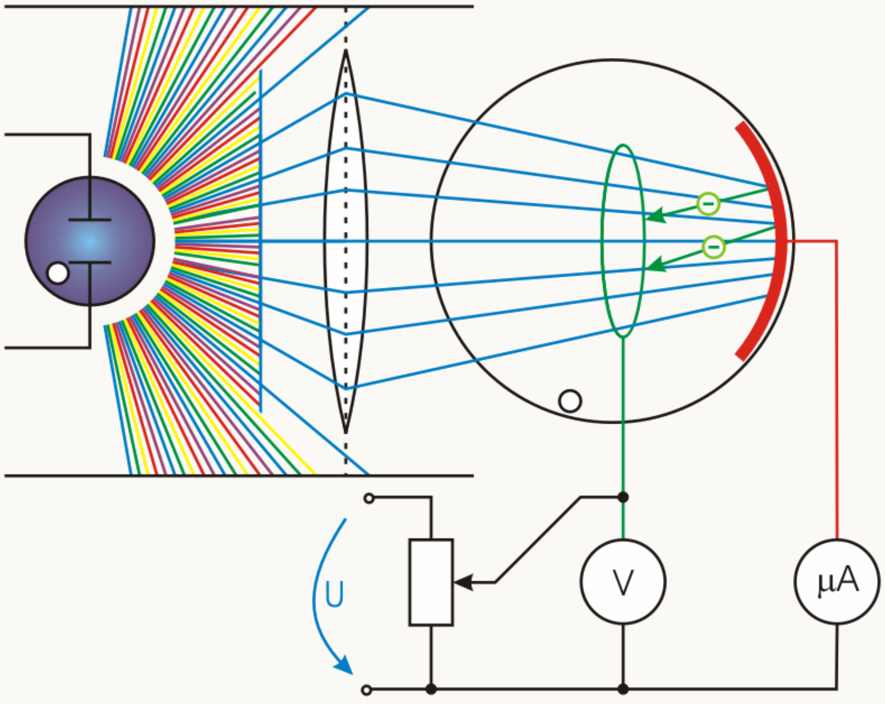


Published in 1905

Nobel Prize for Physics for "his discovery of the law of the photoelectric effect"

Experimental findings on the PE effect

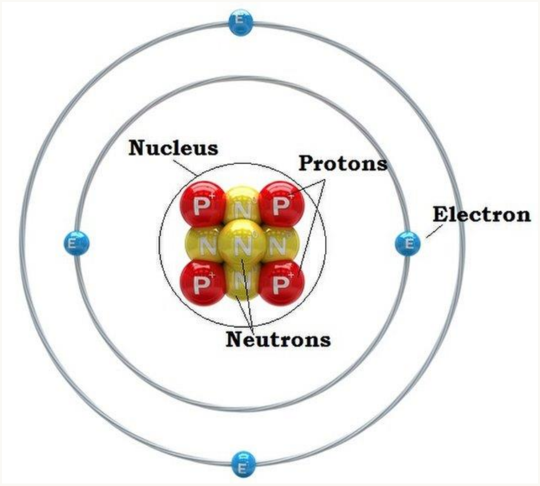
- Electrons released from the target when light of high enough frequency shone (threshold frequency)
- Increasing the intensity of light makes no difference to the threshold frequency
- Increasing the frequency of light increases the current

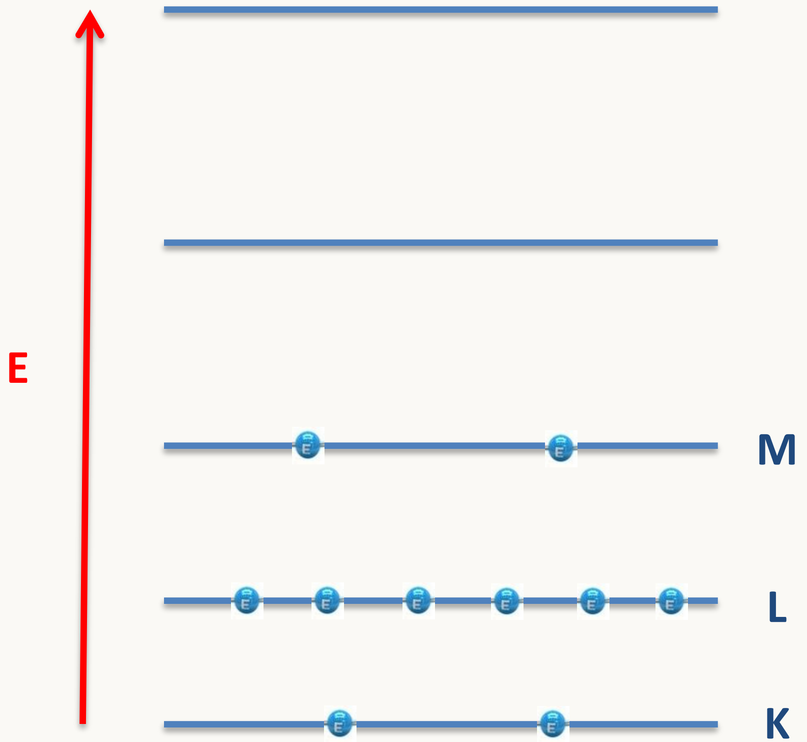


Light travelling in packets (photons) and depositing energy in whole amounts (E = hv)

Electronic energy levels and Binding energy

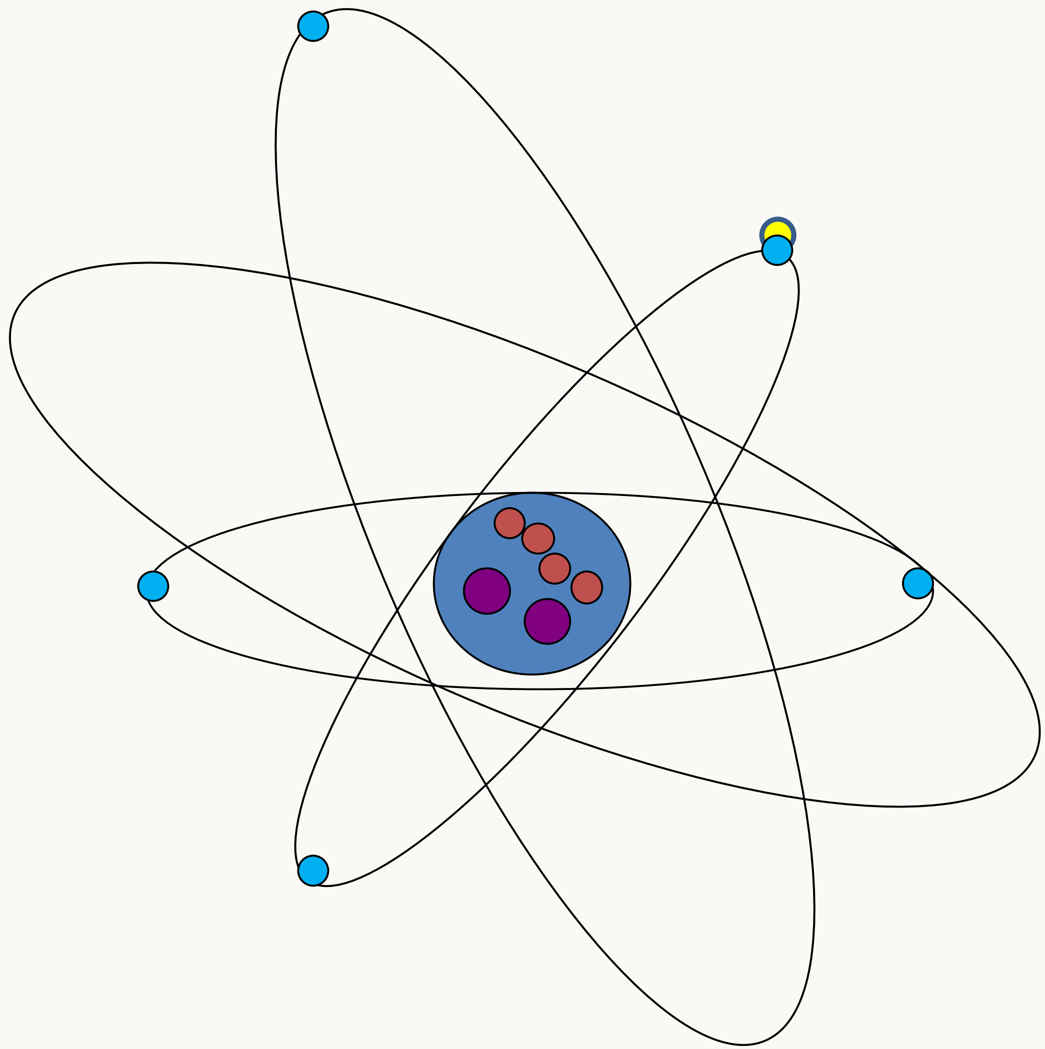
- Electrons that gain energy can jump into a higher orbital





- Binding energy is the energy required to escape the atom

Incident photon has energy equal to or greater than the binding energy of inner bound electron



Photoelectric effect

- Incident photon is completely absorbed by the atom and an inner orbital (normally K-shell) electron
  - The photoelectron is ejected
- Photon energy must be greater than the binding energy of the electron
  - Spare energy is given to photoelectron as kinetic energy

$$KE_{electron} = h\nu - \Phi$$

Φ = binding energy / work function

- The atom is now positively charged and in an excited state due to the vacancy left

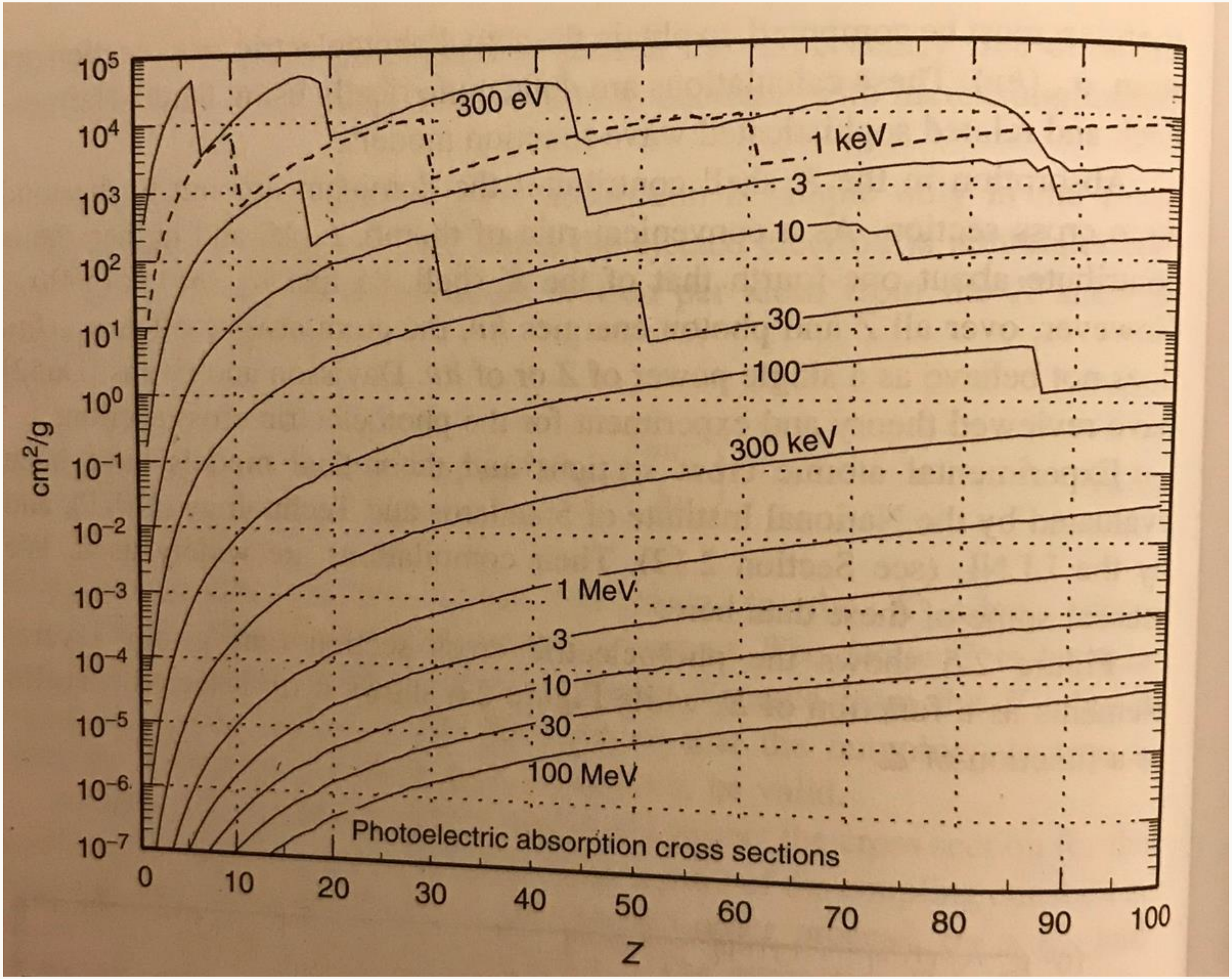
Atomic photoelectric cross section - σ_τ

- A measure of the chance of a PE interaction
- Depends on:

Atomic number of target, Z

- The less tightly bound an electron is the lower σ_τ
  - Hence why ~80% usually comes from k-shell
- Proportional to Z^4
  - High Z means high binding energy

Anyone remember what element/material was used to discover the effect?



300 eV
1 keV
3
10
30
100
300 keV
1 MeV
3
10
30
100 MeV
Photoelectric absorption cross sections
cm²/g
Z

Atomic photoelectric cross section - σ_τ

- Also depends on:

Energy of incident photon, E

The more energetic the photon the more nearly free does the electron appear

  – Therefore higher energy photon means lower σ_τ

- Proportional to ~ $1/E^3$

- at non-relativistic energy

~ 1/E at very-relativistic
How to determine if relativistic or not?

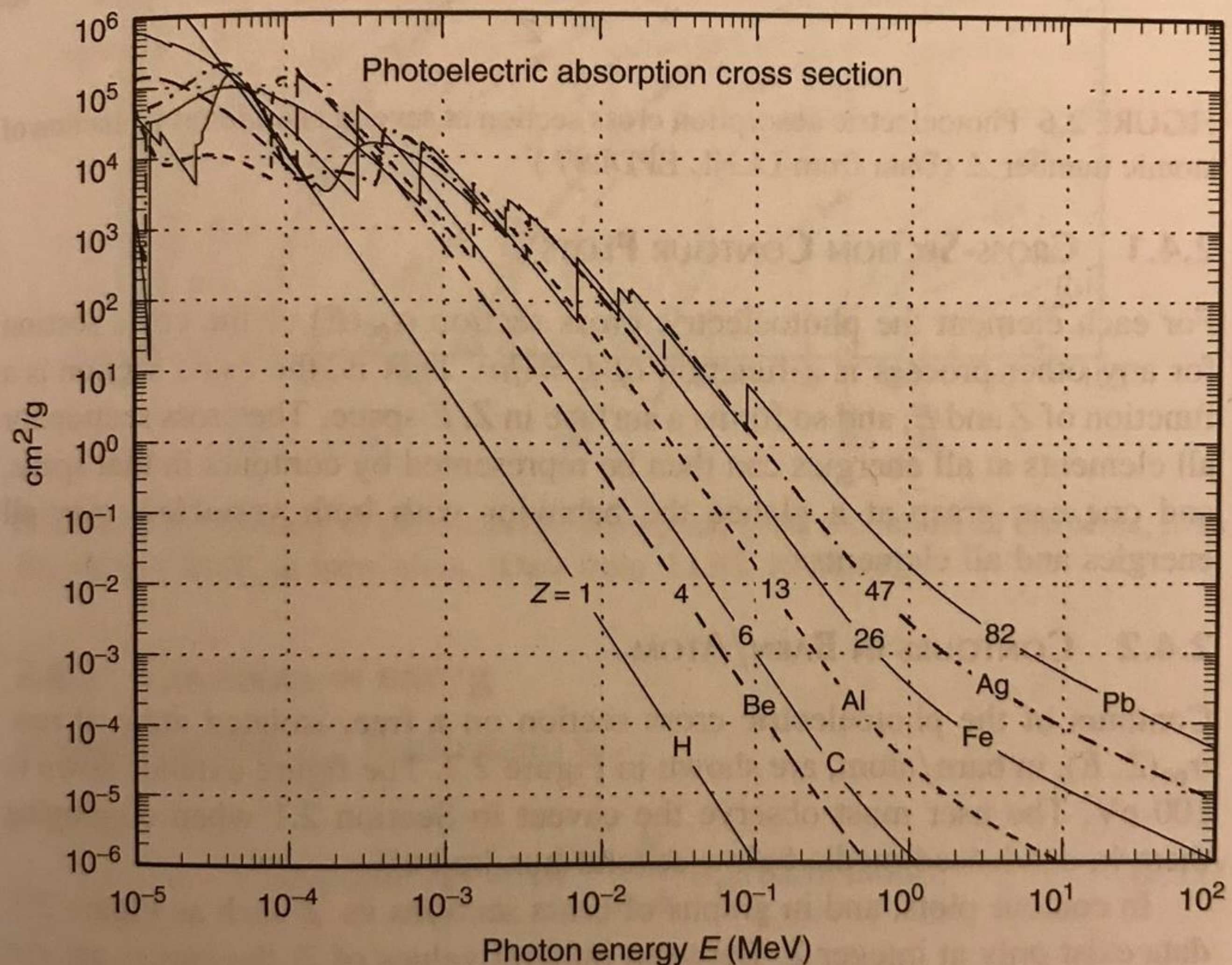
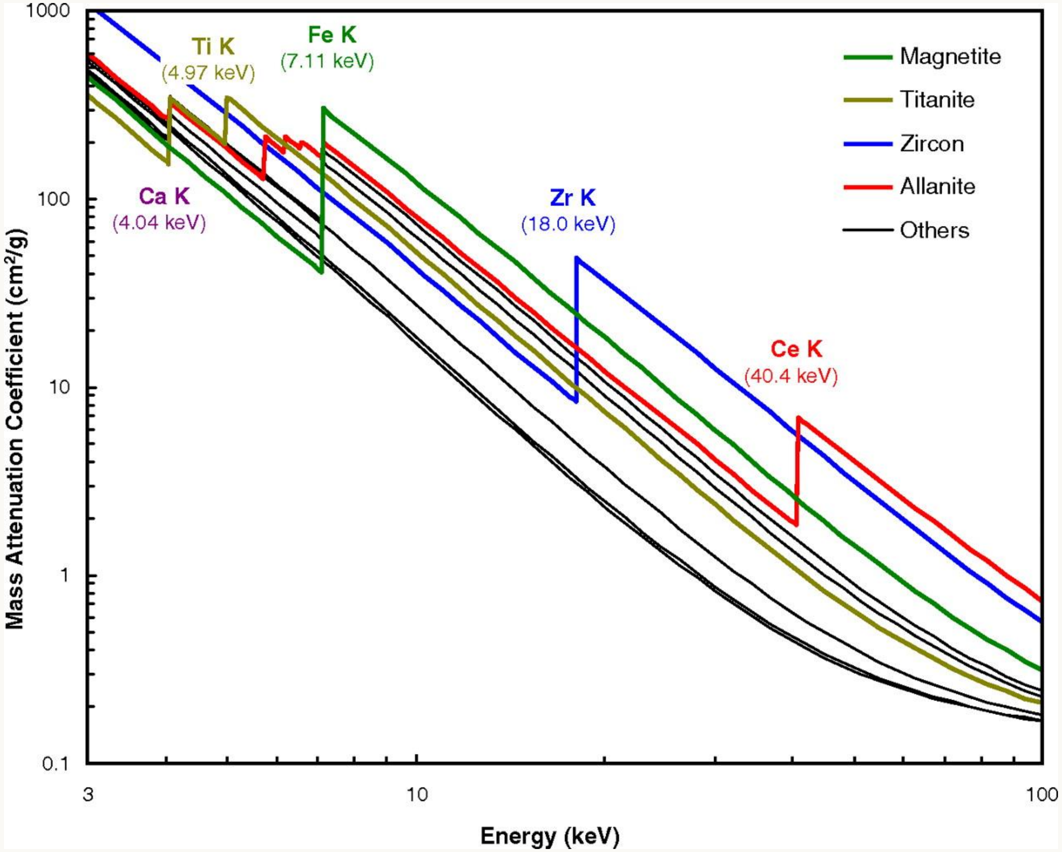


FIGURE 2.5 Photoelectric absorption cross section on several elements as a function of incident photon energy E. (Data from LLNL EPDL97.)

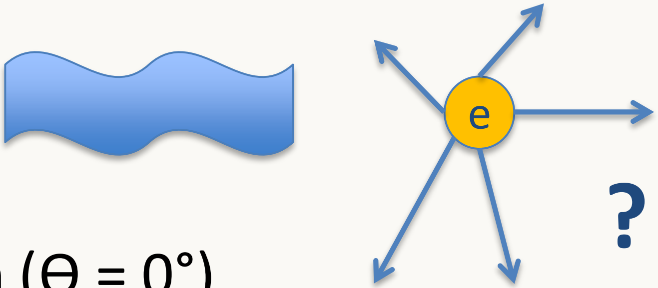
K-edge of different elements

- K-edge
  - Energy above which incident photon has enough energy to free a k-shell electron
  - Dramatic increase in PE cross section
  - Different energy for different elements



Angular distribution of photoelectrons

- Which direction do the photoelectrons come out of the atom?
  - Where is the energy deposited?
  - Could they reach a detector?



- Never in exactly forward direction (ϴ = 0°)
- At low E (<10 keV) tend to be ejected perpendicular to photon direction
- At higher E (>100 keV) photoelectrons are distributed forwards
- Increasing energy forward shifts photoelectrons more

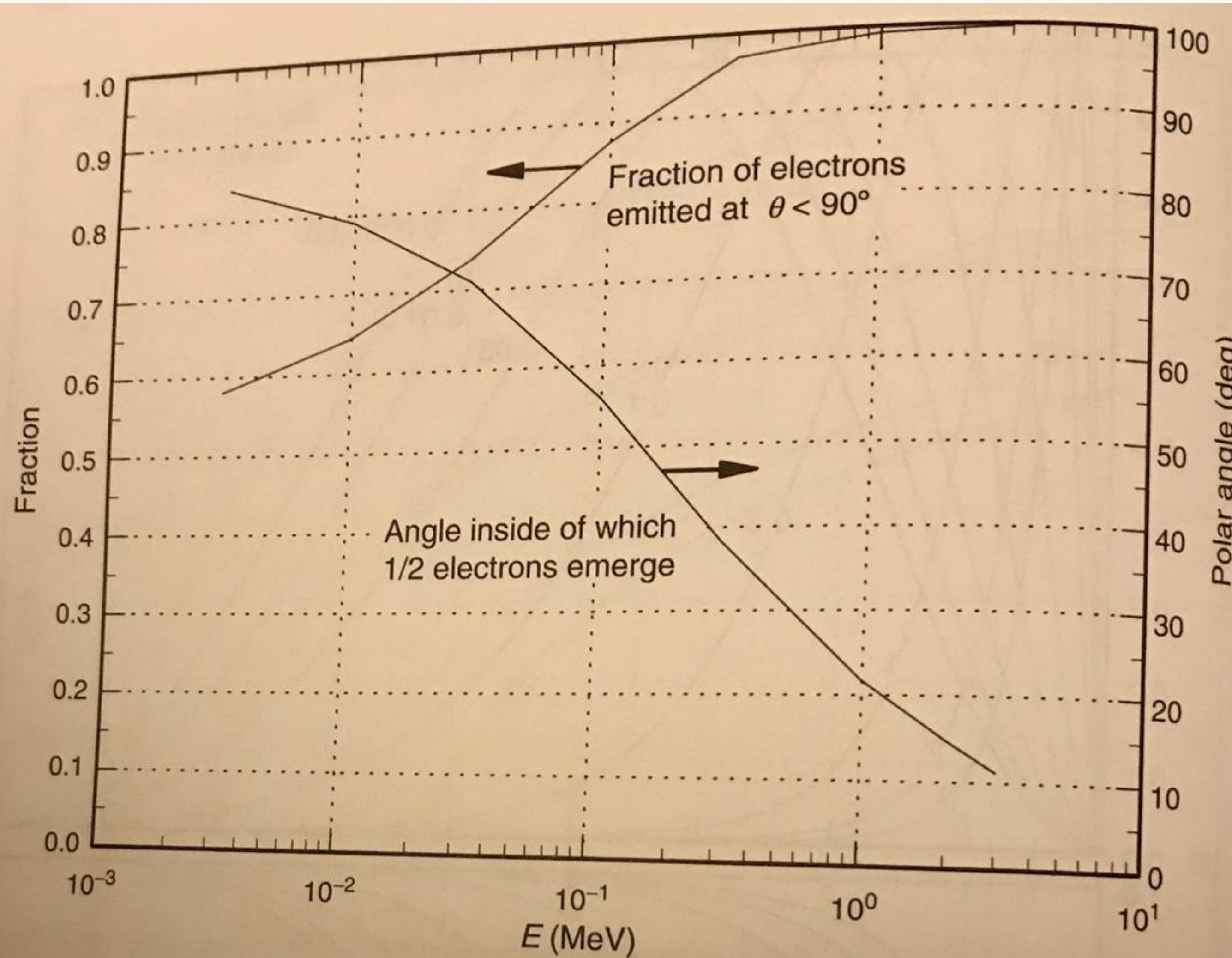


FIGURE 2.12 Summary angles for electron emission in photoelectric absorption. Binding energy is ignored; photon energy = electron energy, so that the abscissa represents either one.

i) Photoelectric effect summary

- Attenuation coeff for PE effect - τ (Tau):

[Approx, based on most simple assumptions]

$$\tau \propto \frac{Z^4}{E^3}$$

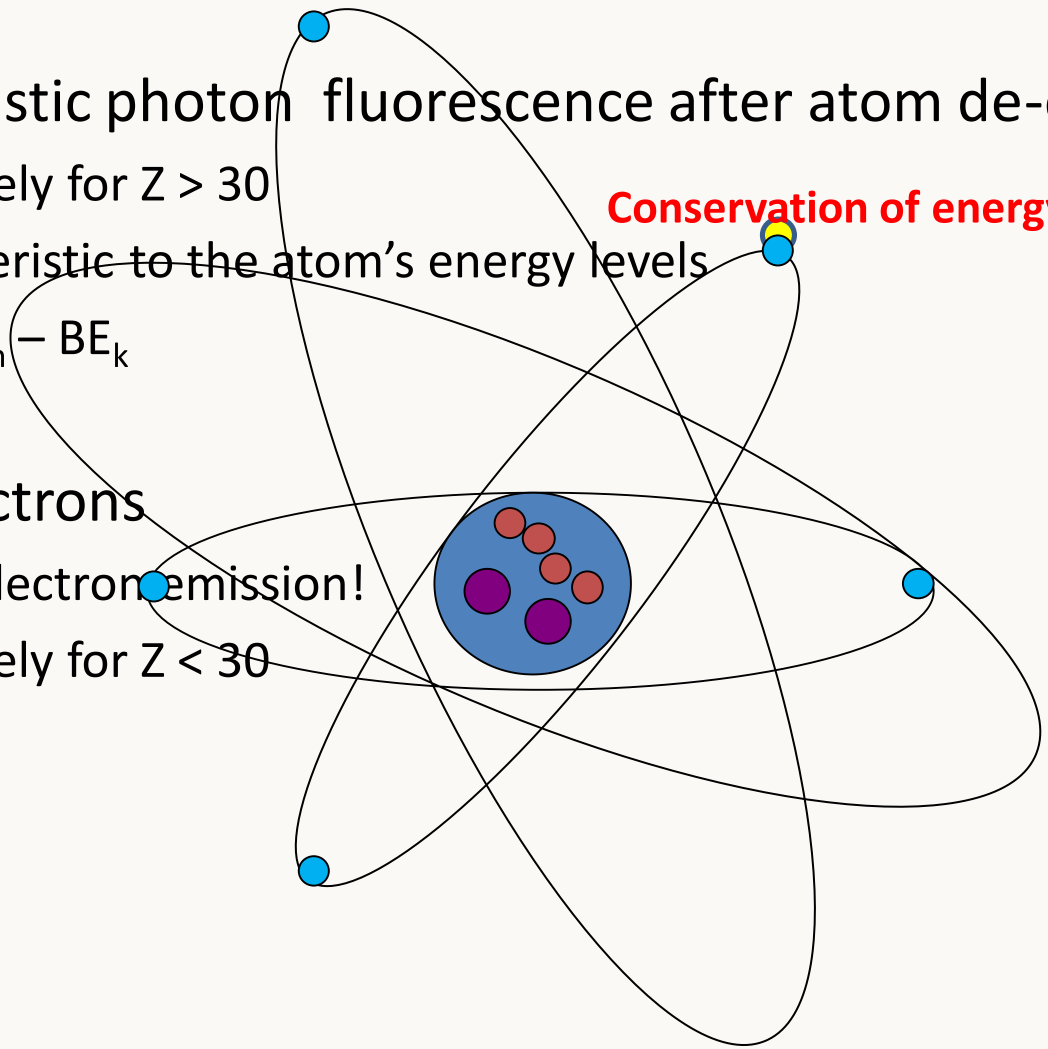
- Occurs at lower energies and high Z materials

- The photoelectric effect is the most important effect for diagnostic images (X-ray tube generation rather than linear accelerator)
  - $Z_{effective}$ - soft tissue = 7.4
  - $Z_{effective}$ - hard tissue = 13.6

Secondary effects of PE

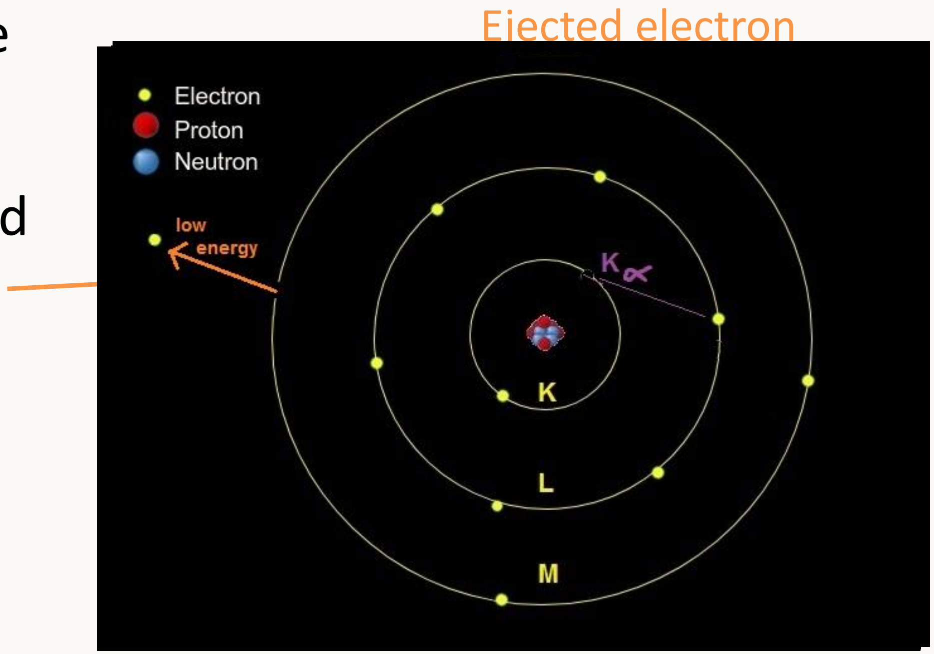
- Characteristic photon fluorescence after atom de-excites
  - Most likely for Z > 30
  - Characteristic to the atom's energy levels
  - $h\nu = BE_m - BE_k$

- Auger electrons
  - Bonus electron emission!
  - Most likely for Z < 30



Auger Electrons

- Once a photoelectron has been emitted the atom will de-excite fluorescing a photon
- This photon has a chance of interacting with a loosely bound outer electron
- The electron gains enough energy to overcome its binding energy
- Known as Auger electrons and has a low kinetic energy, so it does not travel far in tissue
- Cascades are possible!

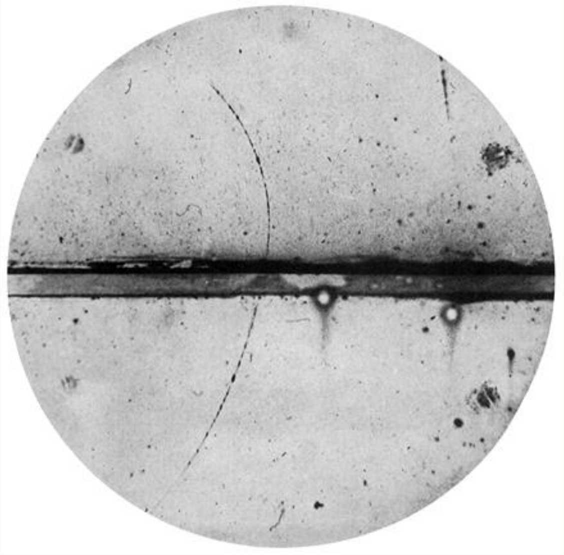


ii) Pair production (absorption)

Patrick Blackett

- First observed in cloud chambers upgrade by →
- Upgraded the Wilson cloud chamber to allow particles to be detected several times per second

Published in 1930s

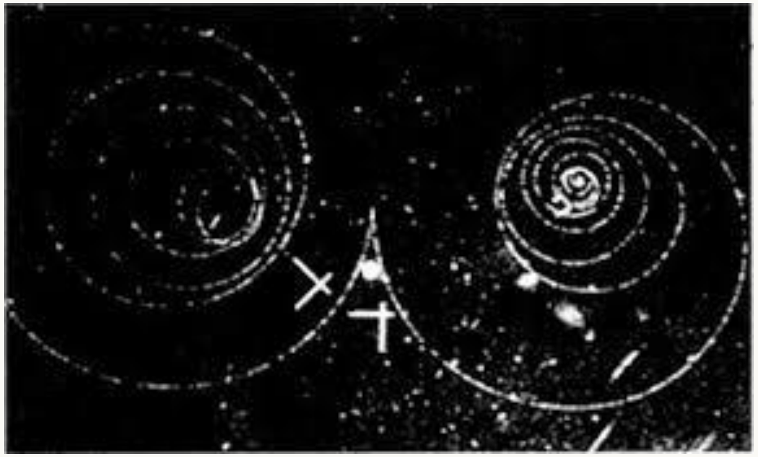


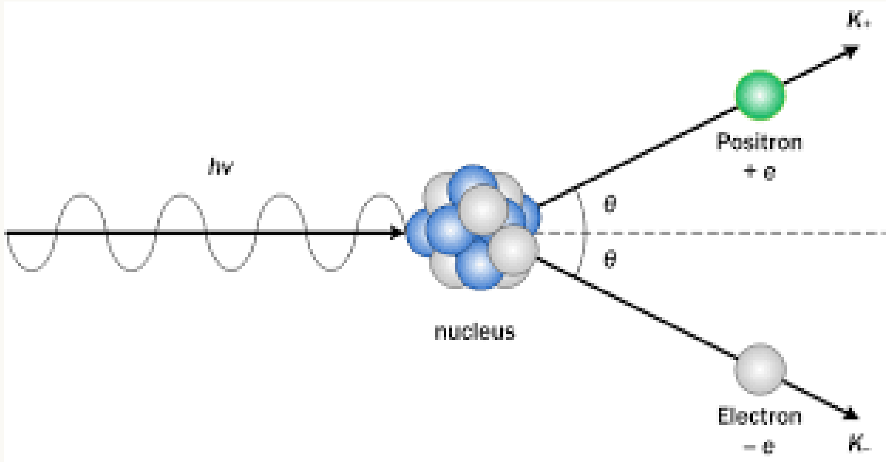
Detection of the positron

Nobel Prize for Physics 1948 "for his development of the Wilson cloud chamber method, and his discoveries therewith in the fields of nuclear physics and cosmic radiation"

Discovery of pair production

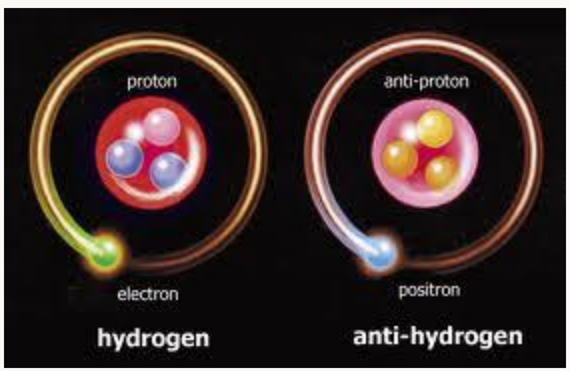
- Charged particles will circle in magnetic field (seen in cloud chamber →)
- Opposite directions indicate oppositely charged particles
- Blackett's upgrade to the cloud chamber allowed it to be seen that both particles had the same origin

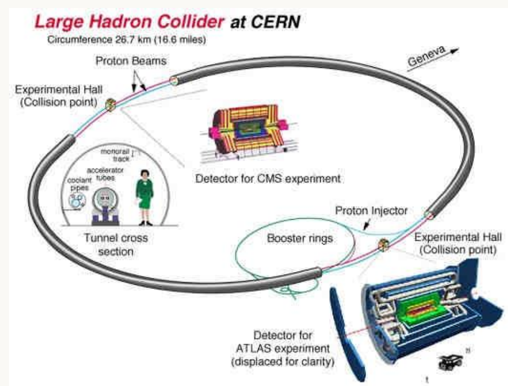


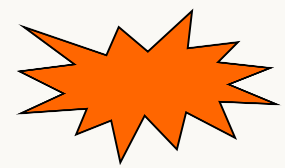


Anti-matter

- All matter particles have an anti-matter counterpart (proton/anti-proton, electron/positron)
- The counterpart has equal mass but opposite charge
- If the matter and anti-matter counterpart meet, they annihilate and release their equivalent-mass energy ($E = mc^2$)







$m = 1.82 \times 10^{-30}$ kg
$E = mc^2$
$= 1.64 \times 10^{-13}$ J

Electron

–

$m = 9.11 \times 10^{-31}$ kg
= 0.511 MeV / c²
$q = -1.602 \times 10^{-19}$ C

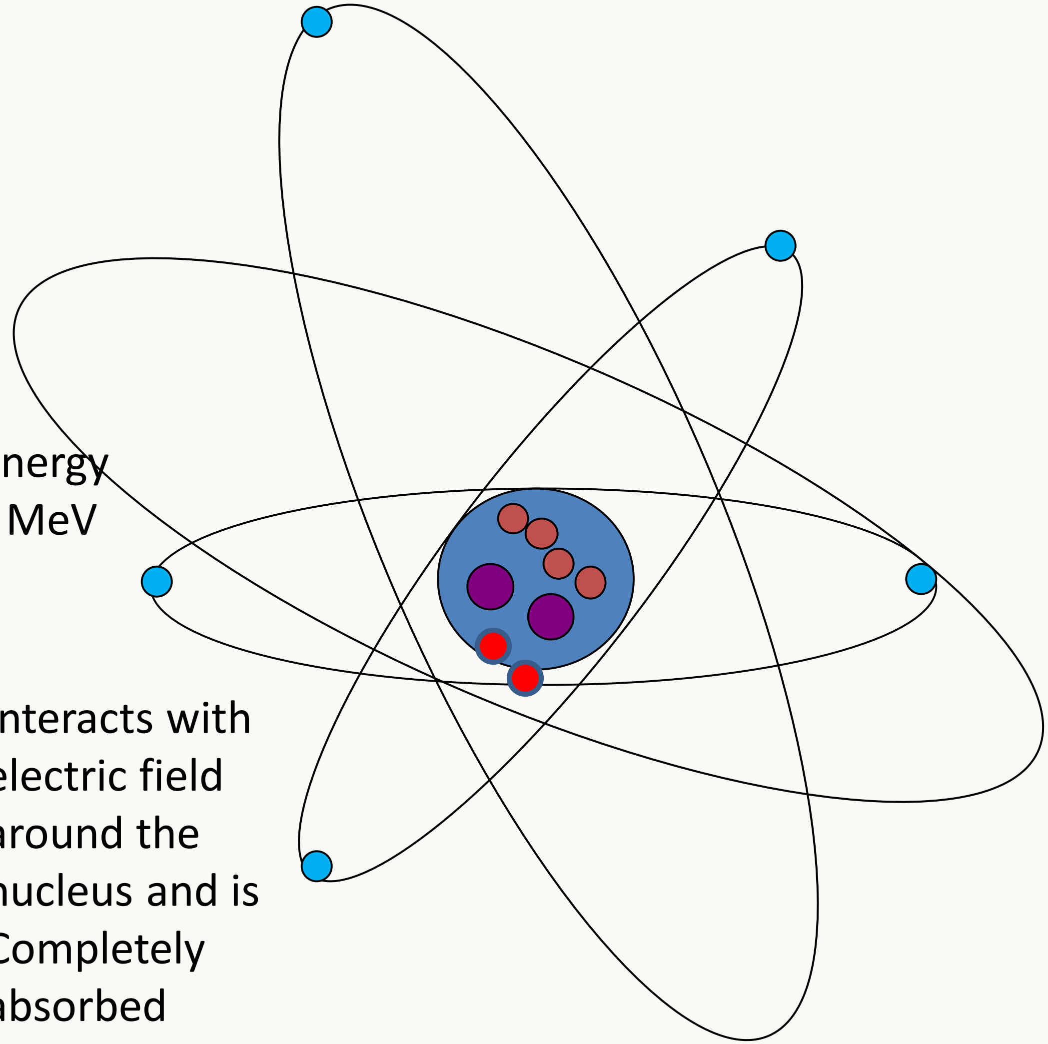
Positron

+

$m = 9.11 \times 10^{-31}$ kg
= 0.511 MeV / c²
$q = +1.602 \times 10^{-19}$ C

e^+

Incoming photon energy greater than 1.022 MeV



Simultaneous creation of two particles:-
POSITRON
ELECTRON

Interacts with electric field around the nucleus and is Completely absorbed

e^-

Pair production

- Incident photon interacts with static electric field of the nucleus
  - Requires enormous fields to create an electron-positron pair
  - Very close nuclear approach required (low σ)
  - Less so at higher photon energies

Why?

- Incident photon must have E of at least 1.022 MeV
  - Not possible below this (σ = 0) but becomes the dominant interaction at very high photon energies

- Nucleus recoils with negligible energy
- Electron and positron carry spare energy as KE

Atomic pair production cross section, σ_K

- A measure of the chance of a PP interaction
- Depends on:

Atomic number of target, Z

- The greater the strength of field the photon enters, the greater the chance of interaction
- Proportional to Z^2

Energy of incident photon, E

- Above the limit of 1.022MeV, the higher the incident photon energy, the greater the chance of interaction
- Proportional to E

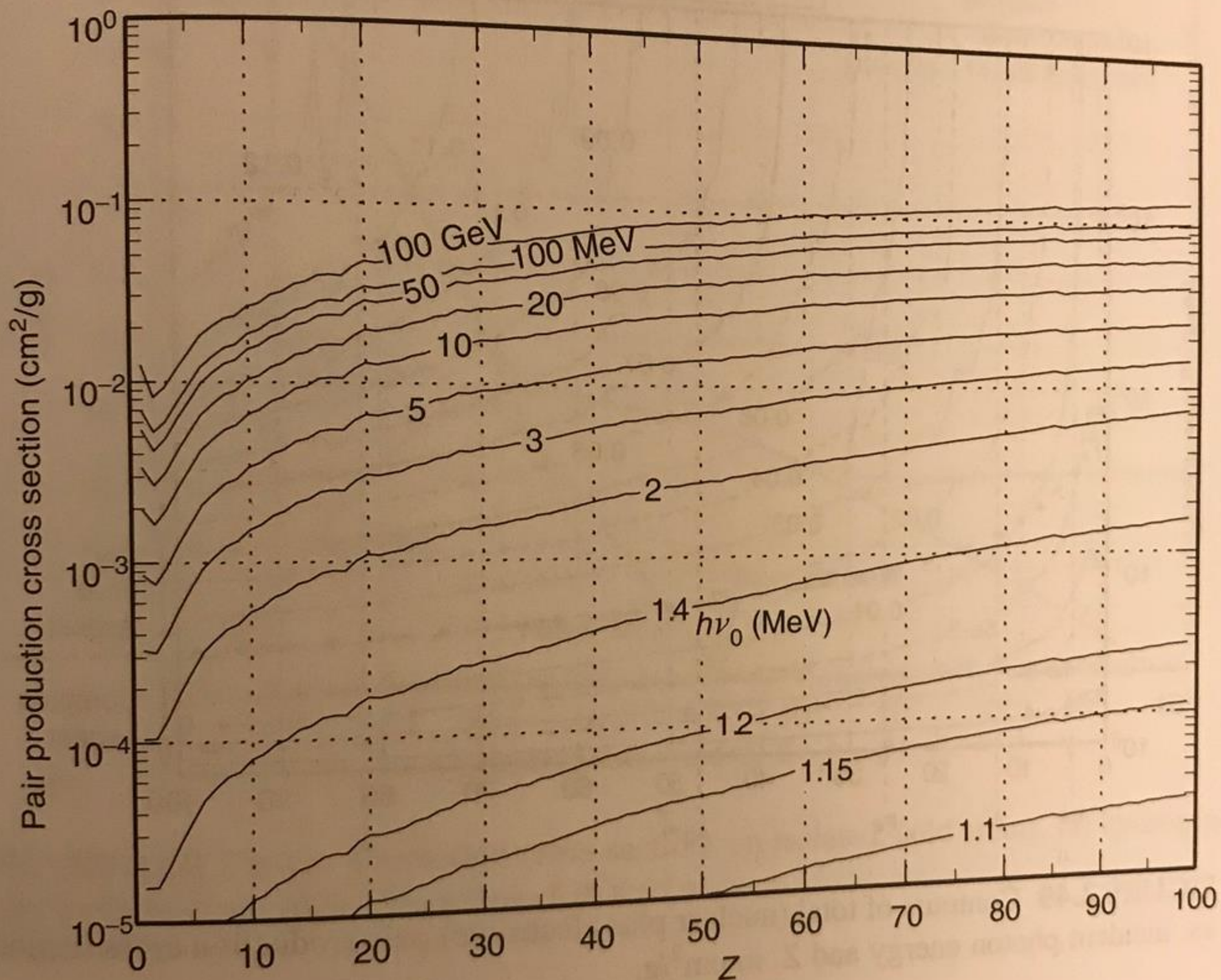


FIGURE 2.47 Total (nuclear plus electronic) pair production cross section for selected incident photon energies vs. Z, in cm^2/g.

ii) Pair production summary

- Attenuation coeff for Pair production - κ (Kappa):

[Approx, based on most simple assumptions]

$$\kappa \propto Z^2 . E$$

Above 1.022 MeV

- Occurs at very high energies and high Z materials

- Becomes the most important interaction for high MegaVoltage (MV) treatment beams (require linear accelerator)
  - Depending on energy of beam, dose can be delivered locally

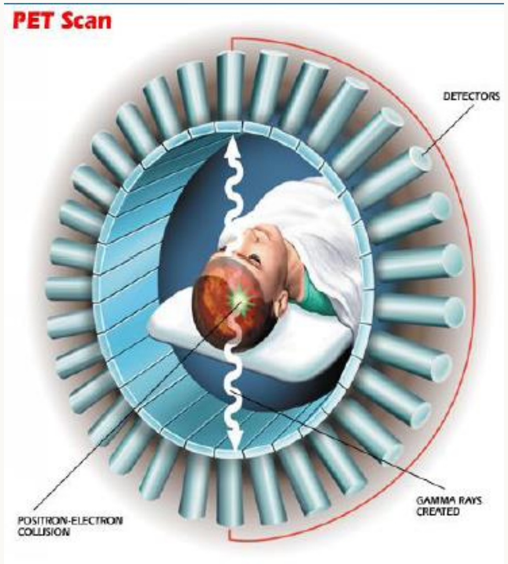
Secondary effects of pair production

- Gamma photon pairs produced from positron interactions
  - Positrons from PP are very short lived
  - Interact with nearby electrons to annihilate and producing 2 photons

Guess the energy of each?

  - Gamma photons must travel in opposite directions (180° to one another) in order to conserve momentum of interaction

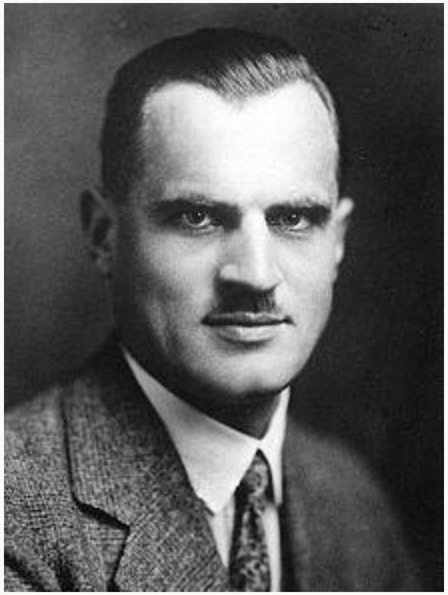
- The principle is used in PET scanning
  - β+ decay occurs releasing positrons
  - Two 180° photons are released simultaneously
  - Back projection algorithms used to find source of interaction

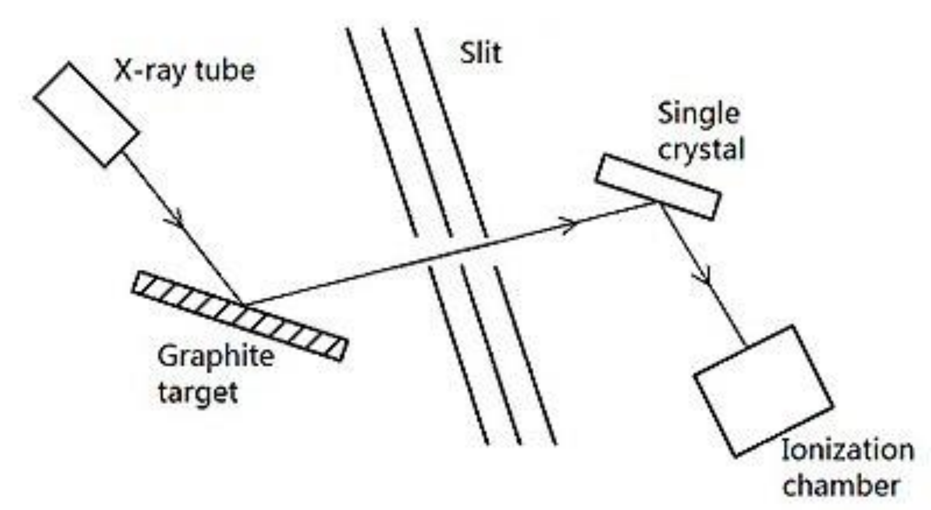


iii) Scattering (mostly Compton)

- First observed in 1923
- An **inelastic** scatter of X-rays off free electrons causing a change in light wavelength known as a “Compton Shift”
- Continued proof of particle nature of light

Arthur Compton



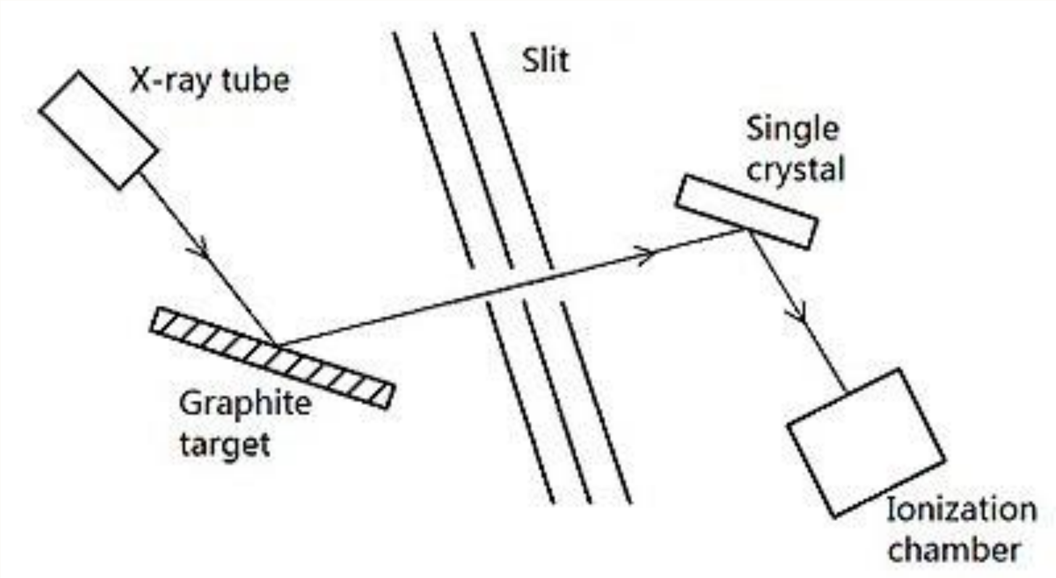


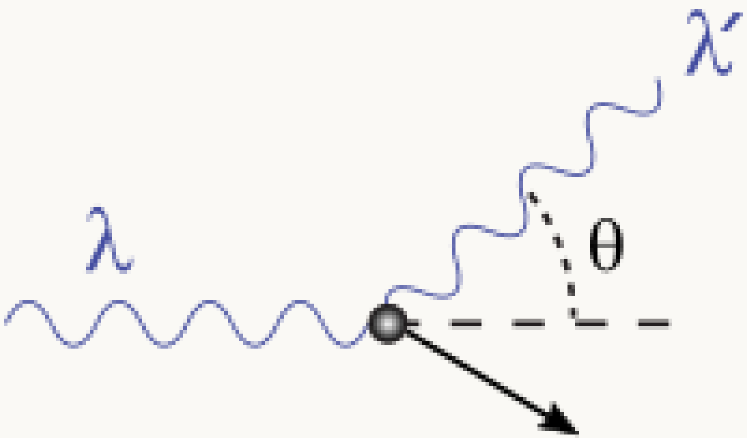
Published in 1923

Nobel Prize for Physics 1927
“for his discovery of the effect named after him”

Compton's findings on the Compton effect

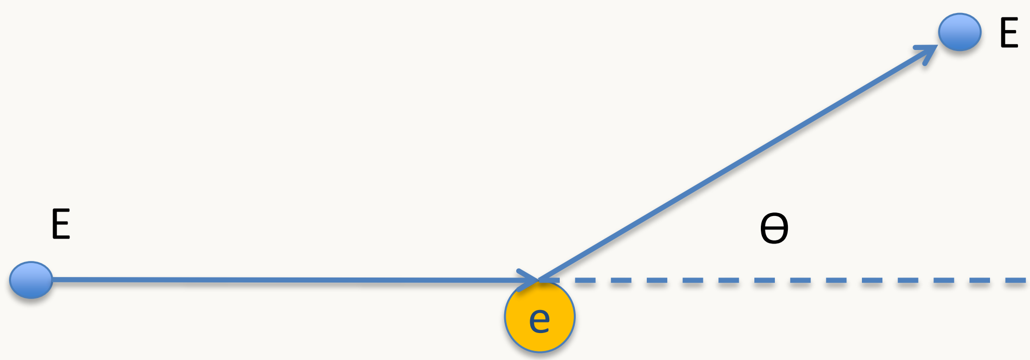
- Incident photons scattered off graphite target lead to an increased wavelength at increased angles
- Tested at low intensity to dismiss chance of being a Doppler shift
- Thus showing that light behaves as if consisting of a stream of particles with energy proportional to its frequency





Elastic photon scattering

- Sometimes known as coherent of classical scattering
- Photon changes direction on interaction without losing energy



- 2 types worth being aware of (these scattering effects are most common at low energy, but still significant at higher energy)

Elastic scatter examples

Thompson scattering

- Incident photon interacts with an oscillating atomic electron
- Prompt emission of photon with **same wavelength**
- Net effect - change in direction with no transfer of energy to medium

Rayleigh scattering

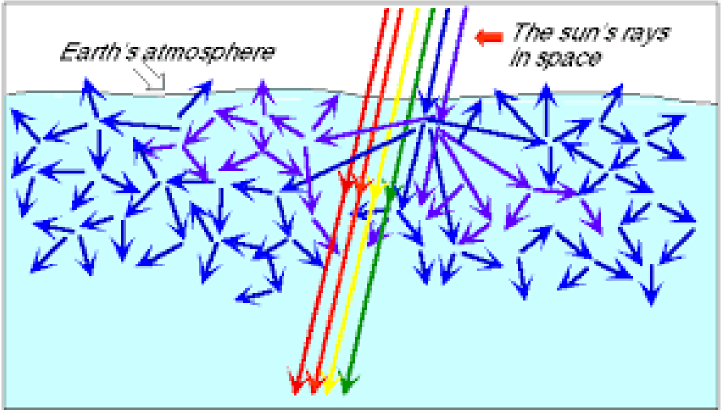
- Incident photon interacts with whole atom causing bound electrons to vibrate
- Prompt emission of photon with **same wavelength**
- Scatter occurs mainly in forward direction

Elastic scatter summary

- Attenuation coeff for elastic scatter - ϕ (Phi):

[Approx, based on most simple assumptions]

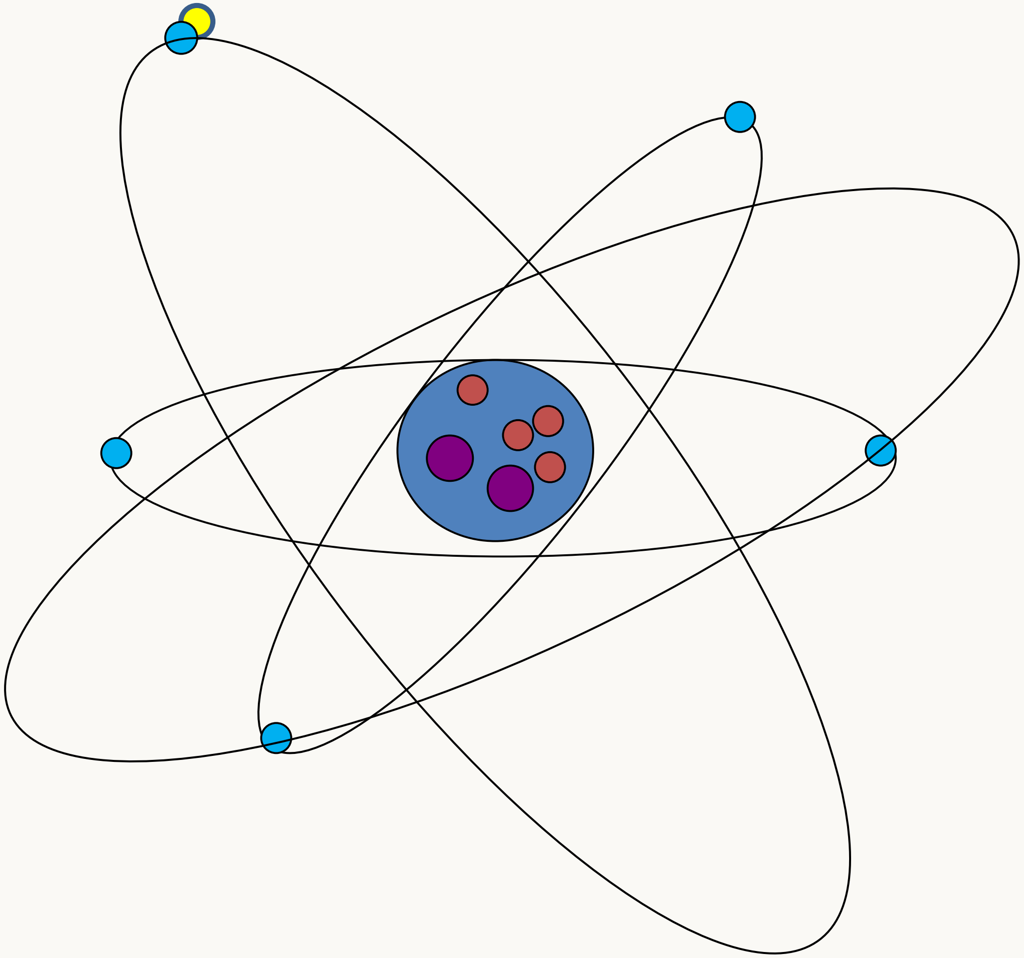
$$\phi \propto \frac{Z^2}{E}$$



- Occurs at lower energies and high Z materials

- This scattering is a minor (but significant) contributor to the attenuation process, and no contribution to absorption (no energy lost)

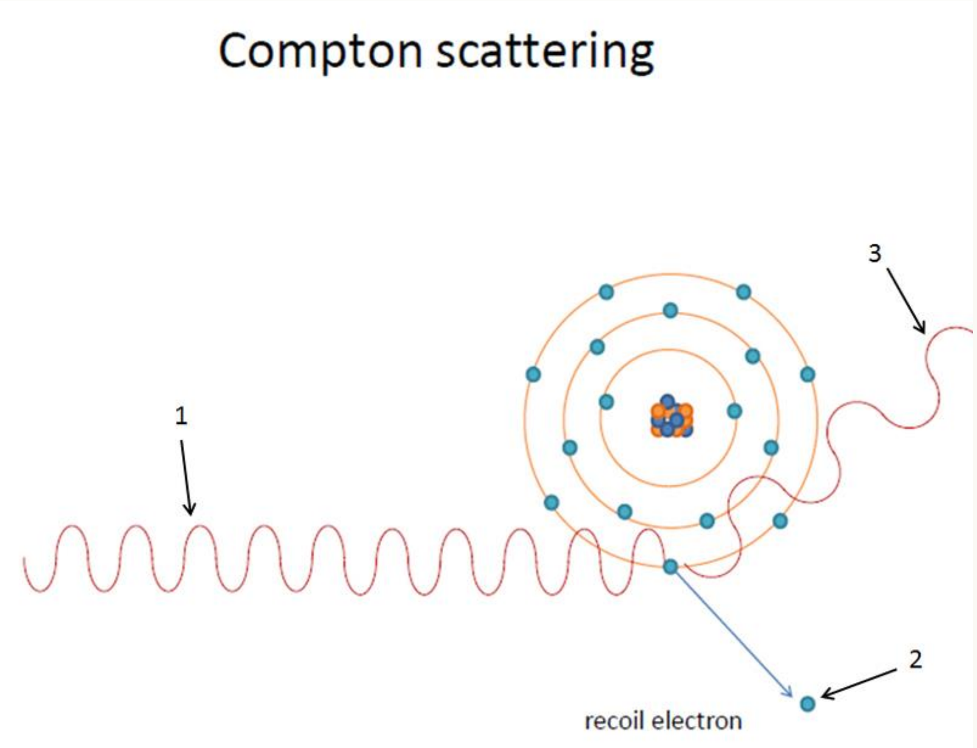
Compton Scattering



The incident photon interacts with an outer shell electron and shares its energy between the recoil electron and scattered photon

Compton Scattering

- Also known as incoherent or inelastic scattering
- Incident photon ejects an outer electron of an atom and a photon of lower energy is scattered from the atom



Atomic Compton scatter cross section, σ_σ

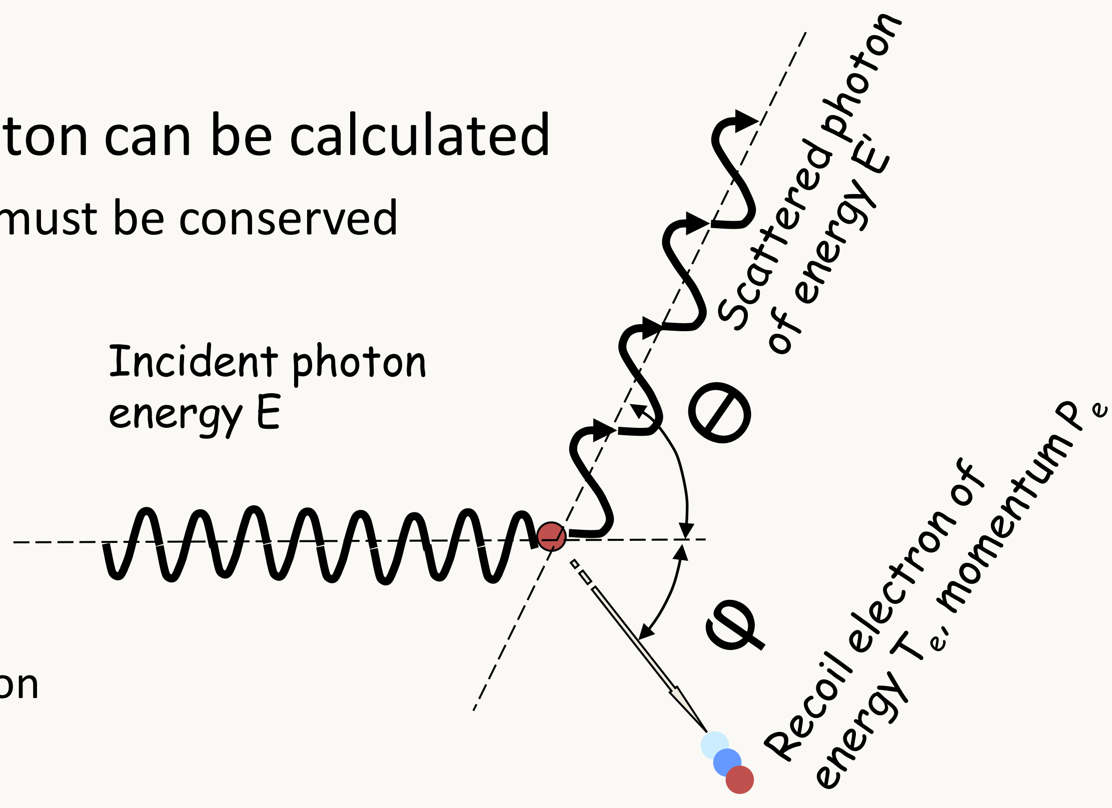
- A measure of the chance of a Compton scatter interaction
- Depends on:
  - Having a high enough electron density
  - Being more dominant than PE effect
  - Energy of incident photon, E

$$\sigma_\sigma \propto \frac{1}{E}$$

Compton shift

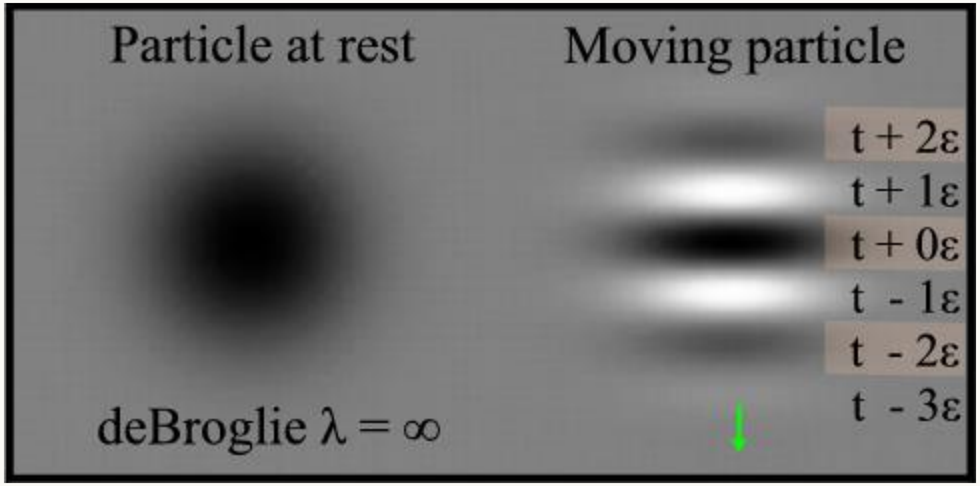
- Change in wavelength (or energy) of incident photon after a Compton scatter

- Energy of scattered photon can be calculated
  - Energy and momentum must be conserved



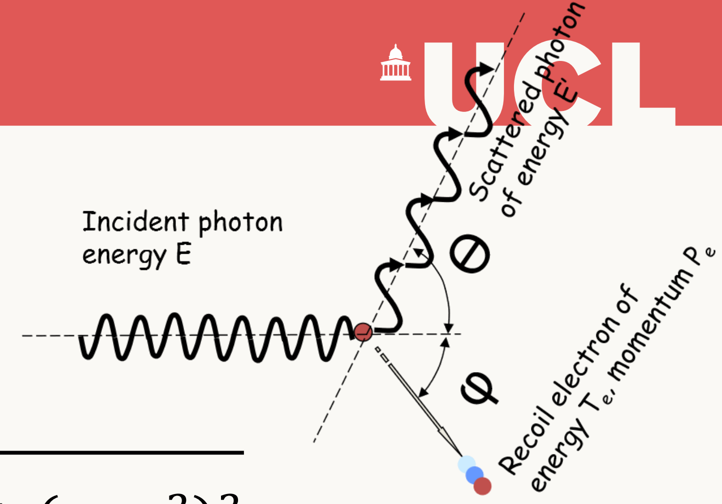
E' = energy of scattered photon
E = energy of incoming photon
m_e = rest mass energy of the electron
c = speed of light

De Broglie wavelength/momentum relation



$$p = \frac{h}{\lambda} = \frac{hv}{c}$$

Compton shift equation



Energy conservation

(1) $$h\nu_i + m_e c^2 = h\nu_f + \sqrt{p_e^2 c^2 + (m_e c^2)^2}$$

Momentum conservation

(2) $$\frac{h\nu_i}{c} = \frac{h\nu_f}{c} cos\theta + p_e cos\varphi$$ Resolving x-direction

(3) $$\frac{h\nu_f}{c} sin\theta = p_e sin\varphi$$ Resolving y-direction

Resolve these equations – easier to use dot product [not examinable]

$$\boldsymbol{p_{p,i}} = \boldsymbol{p_{p,f}} + \boldsymbol{p_e}$$ - Vector notation

Compton equation (s)

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

- Scattered photon energy

$$\lambda_f - \lambda_i = \frac{h}{m_e c}(1-\cos\theta)$$

- Compton (wavelength) shift

$$T = E_i - E_f$$

- Recoil electron energy

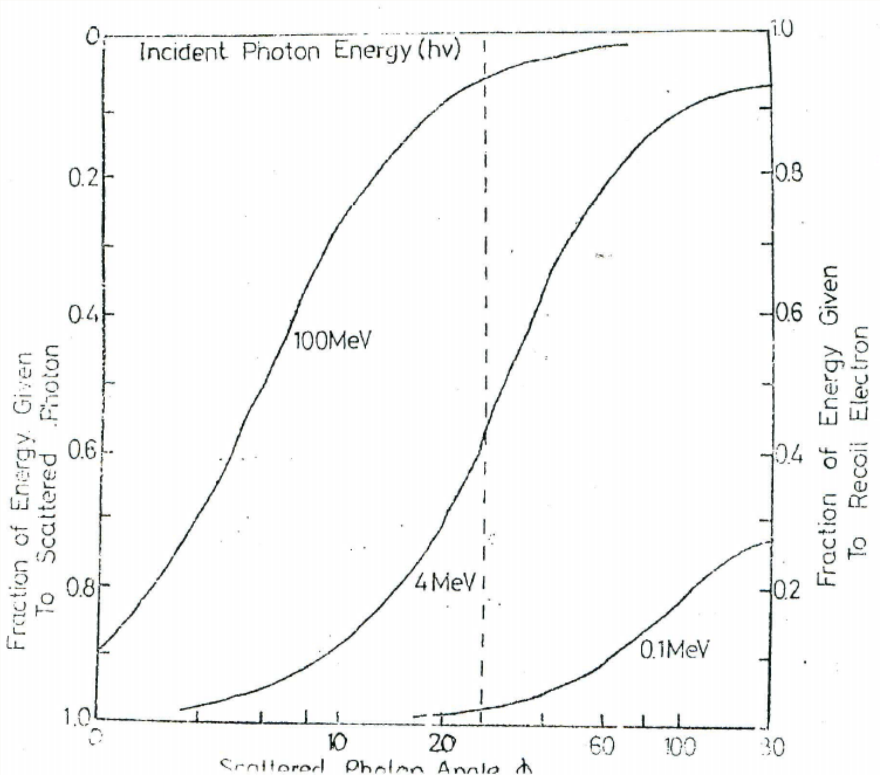
- Pro-tip:
  - Keep energy in eV
  - Know rest energy of electron, $m_e c^2$ = 511keV

Example

- A 1.332-MeV gamma photon from ^{60}Co is Compton scattered at an angle of 140°. Calculate the energy of the scattered photon and the Compton shift in energy and wavelength

Relationship between scatter angle and Energy loss

- Greater the scatter angle (up to 180°) the greater the loss of energy
- Highest energy possible lost in a back-scatter
  - **Why? Look at the Compton eqn**



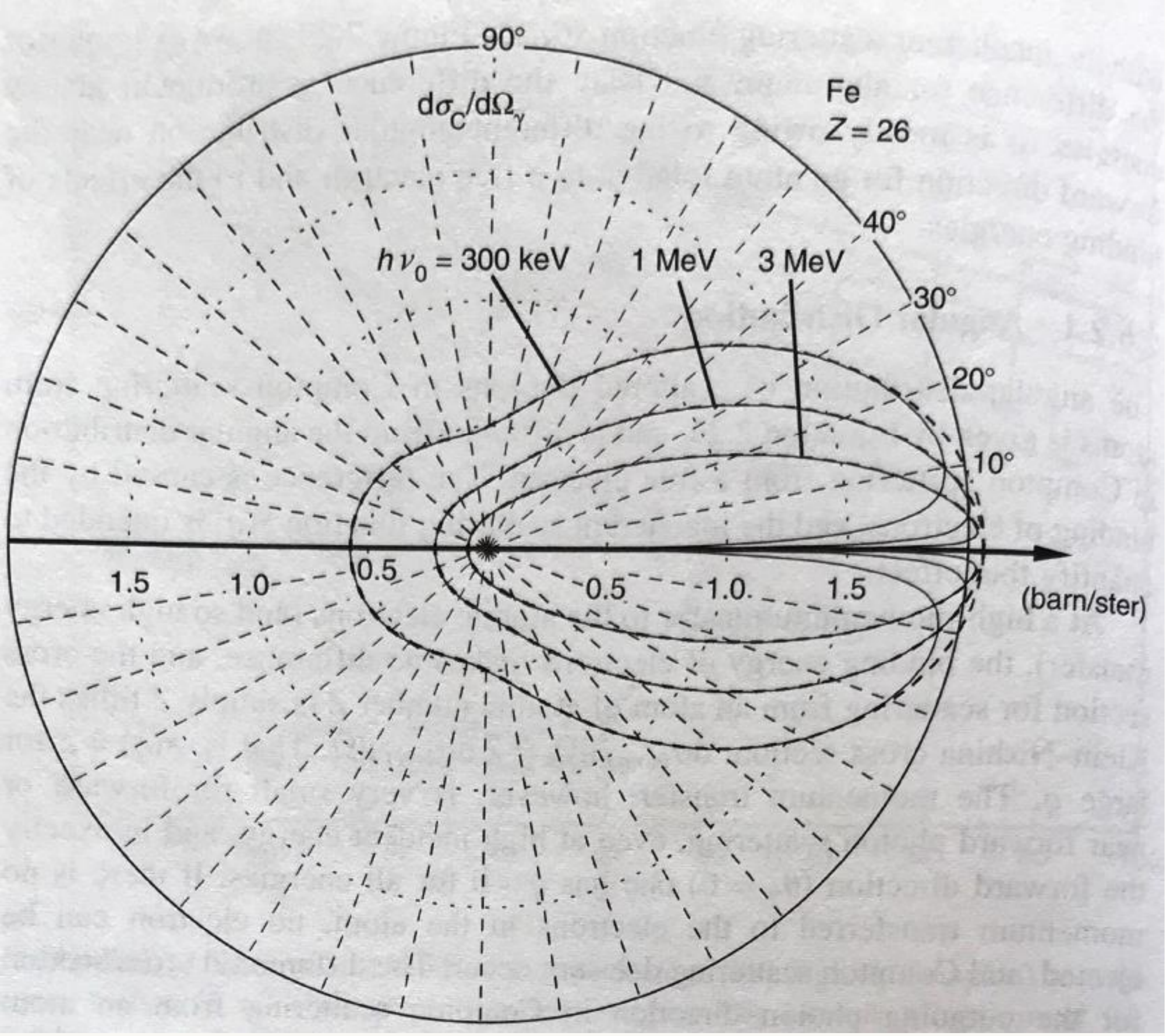
Klein-Nishina formula

- Gives the differential Compton scattering cross section
  - The probability of a photon Compton scattering to a particular angle

$$\frac{d\sigma}{d\Omega} = \frac{r_e^2}{2}(1 + \cos^2\phi)\left[\frac{1}{1 + \alpha(1 - \cos\phi)}\right]^2 \cdot \left\{1 + \frac{\alpha^2(1 - \cos\phi)^2}{[1 + \alpha(1 - \cos\phi)](1 - \cos^2\phi)}\right\}$$

  - Where $\alpha \equiv E/m_e c^2$ and r_e is the classical electron radius.
  - You will see this again (and hopefully validate it!) in the Detector practicals

Compton differential cross section for scattered photon on atomic Fe at three incident energies. Dashed line represent KN relation



iii) Compton scatter summary

- Attenuation coeff for Compton scatter - σ (Sigma):

$$\sigma \propto \frac{1}{E}$$

[Approx, based on most simple assumptions]

- Occurs at mid to high energies and in higher Z materials

- At energies of 100 keV - 10 MeV the dominant interaction of radiation is the Compton effect

Summary of Attenuation of Photons in Matter

- Photoelectric Effect: $\tau \propto \frac{Z^4}{E^3}$
  - Dominates at low photon energies, especially high atomic number materials
- Compton: $\sigma \propto \frac{1}{E}$
  - Dominates at medium photon energies, especially low atomic number materials
- Pair Production: $\kappa \propto Z^2.E$
  - when hν >1.02 MeV
  - Dominates at very high photon energies, especially high atomic number materials
- Total attenuation coefficient $\mu = \tau + \sigma + \kappa \quad (+\sigma_{coh})$

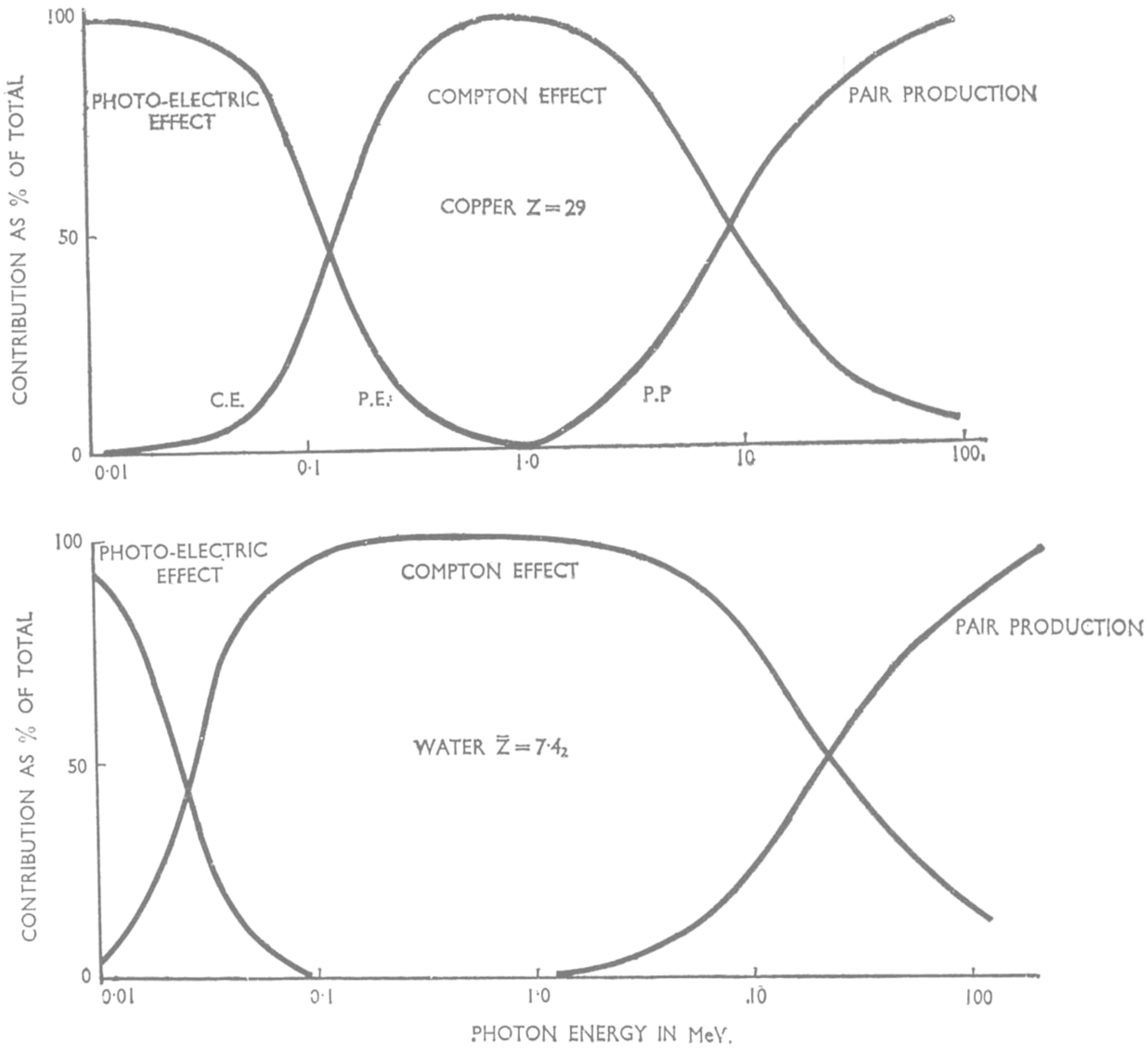
Relative contributions

High atomic number
Z = 29

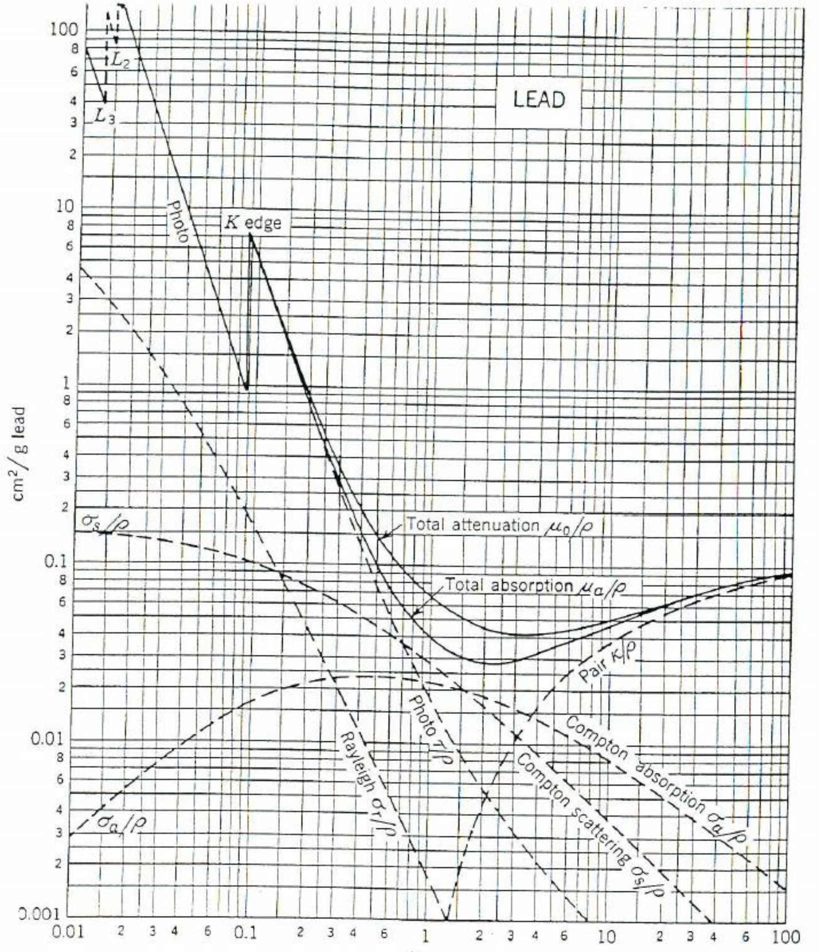
(metal)

Low atomic number
Z =7.4

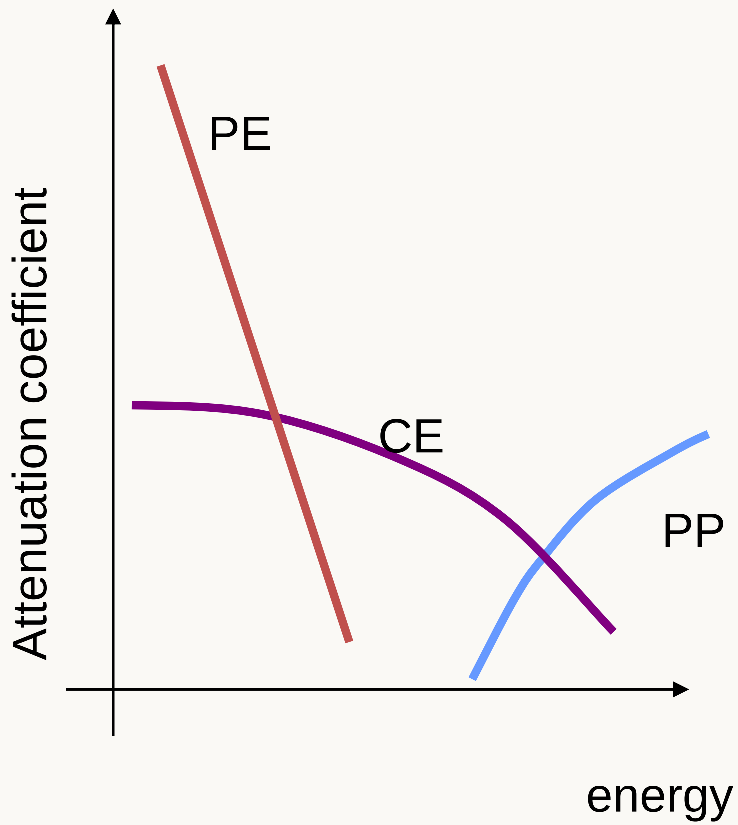
(water Z_{eff})



Combined interactions



Mass attenuation coefficients for photons in lead.



The general behaviour is shown above

Image quality in photon imaging

Low transmission
(high skin dose)

Good contrast
(photoelectric effect
$\mu \propto z^4$)

Mammography

Acceptable signal and contrast

Compton effect

X-ray imaging

CT - imaging

High signal

Reduced contrast

Reduced image quality

High doses

30kev **80kev** **120kev** **1Mev**

Misconceptions on photon interactions

- For a beam of incident photons, multiple types of interaction can happen simultaneously to different photons in the beam
- The photoelectric effect, Compton scatter and pair production all deposit energy.
  - Where that energy is absorbed depends on secondary interactions

Dosimetry implications of photon interactions

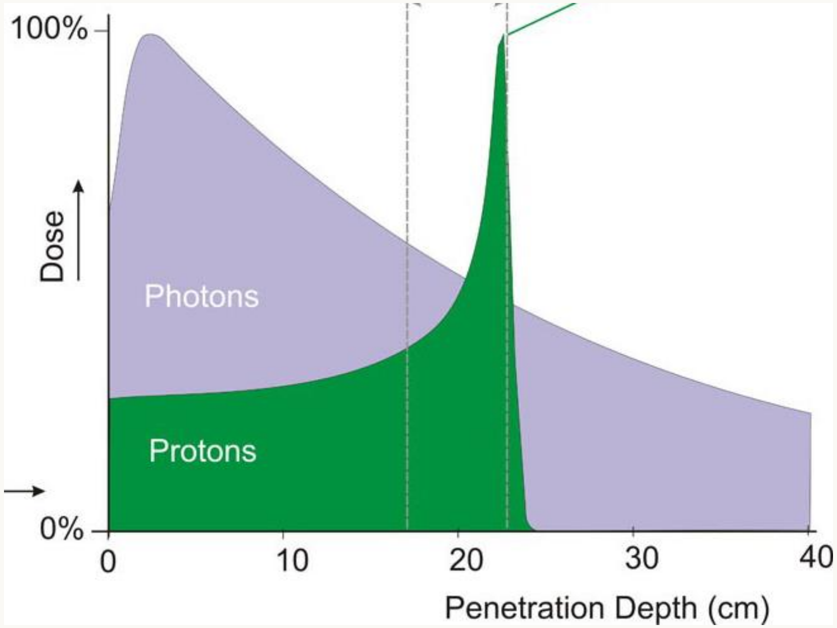
- Photoelectric effect
- Compton scatter
- Pair production
- Coherent scatter

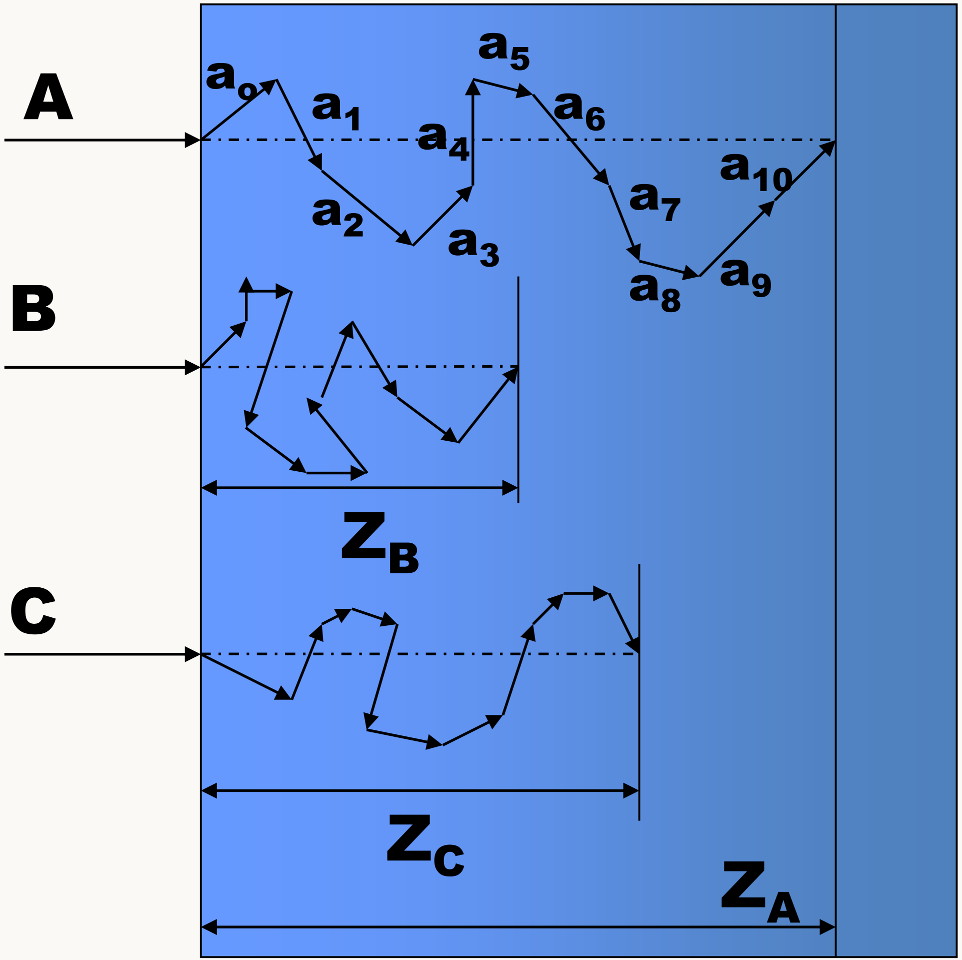
Detector implications of photon interactions

- Photoelectric effect
- Compton scatter
- Pair production
- Coherent scatter

Next time

1. Charged particle interactions





Any Questions?

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