Queen Mary
University of London
Science and Engineering

Radiation Detectors (SPA 6309)

Lecture 3

Last revised 26 January 2020

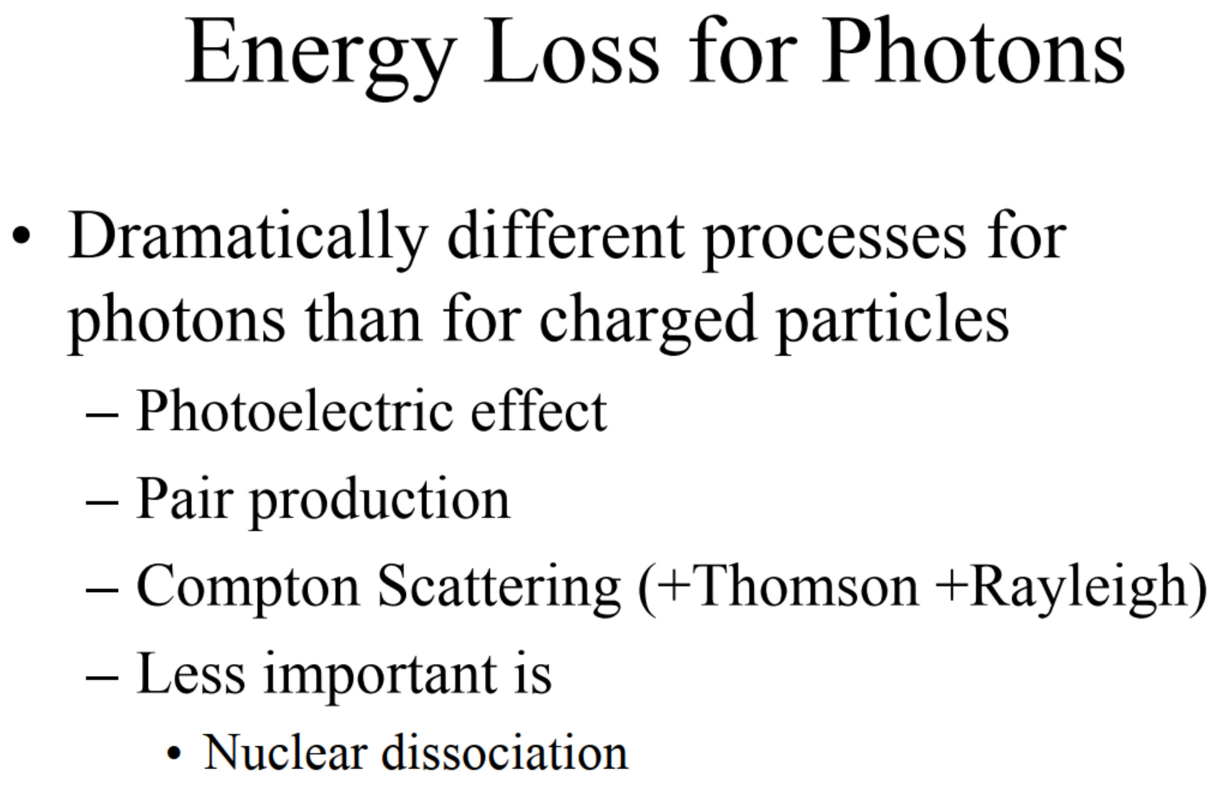
What is this lecture about?

- The principles of detection of ionising radiation
    - Interaction of charged and neutral particles with matter
    - Gaseous sensors
    - Semiconductor sensors
    - Scintillators
- Sensor systems used in particle and nuclear physics
    - Calorimeters
    - Tracking detectors
    - Neutrino detectors

Key points from previous lecture

- The principles of detection of ionising radiation
  - Bethe-Bloch formula and the concept of the Minimum Ionising Particle (MIP).
  - ~ 2 MeV $g^{-1}cm^{2}$ is the key number to retain in your mind, for relativistic particles and all materials (except H).
  - Bragg curve for ionising particles, most energy per unit length deposited at the end of their range (used in proton radiation cancer therapy).
  - Electrons lose energy dominantly by bremsstrahlung (gamma radiation) above the *critical energy* which is in the range 115 to 7 MeV for the elements Be to U.

Photons



Energy Loss for Photons

- Dramatically different processes for photons than for charged particles
  - Photoelectric effect
  - Pair production
  - Compton Scattering (+Thomson +Rayleigh)
  - Less important is
    - Nuclear dissociation

Photons

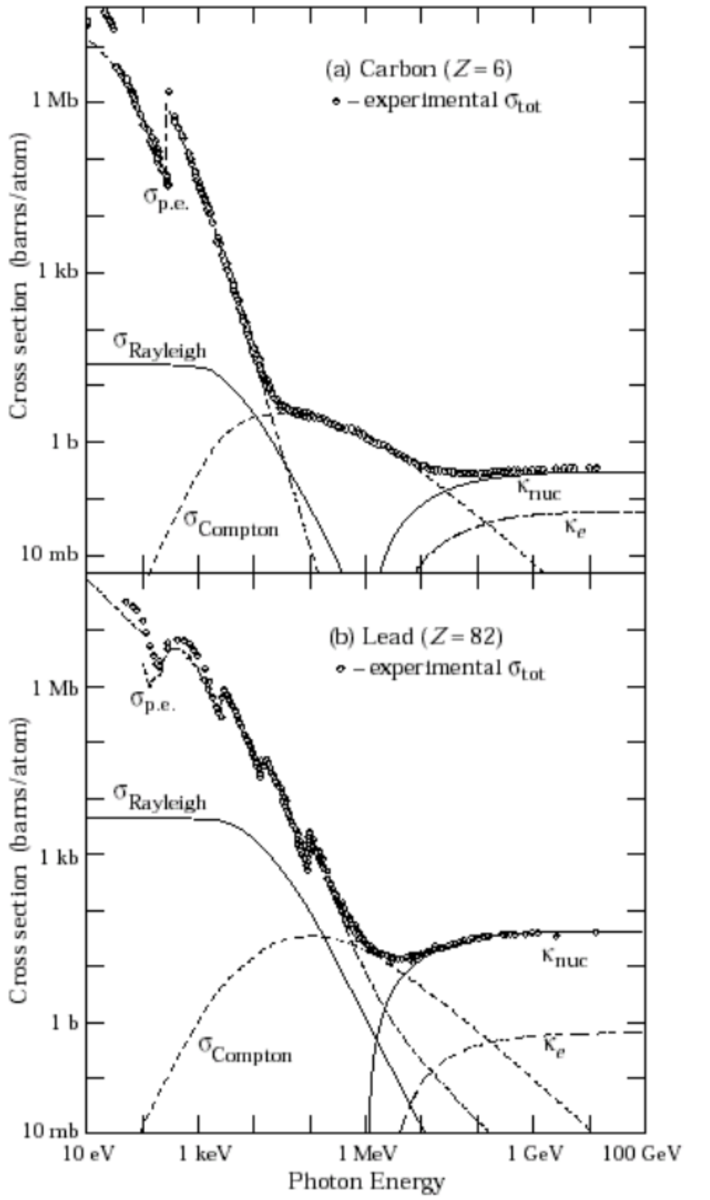
Dominant interaction below ~ 100 keV

- Photoelectric effect
  - Absorption of a photon by an atomic electron followed by the subsequent ejection of an electron from the atom.
  - Nucleus absorbs the recoil momentum
  - For photon energies above the K-shell the absorption cross section varies approximately as Z^5
  - *Implies that high Z materials make good gamma ray detectors* e.g. NaI, BGO, CsI (all scintillating crystals).

NOTE: These comments regarding the photoelectric effect is relevant up to photon energies ~ a few 100 keV

Photons

Photon absorption cross-sections in Carbon and Lead



1 barn = 10^{-24} cm^2

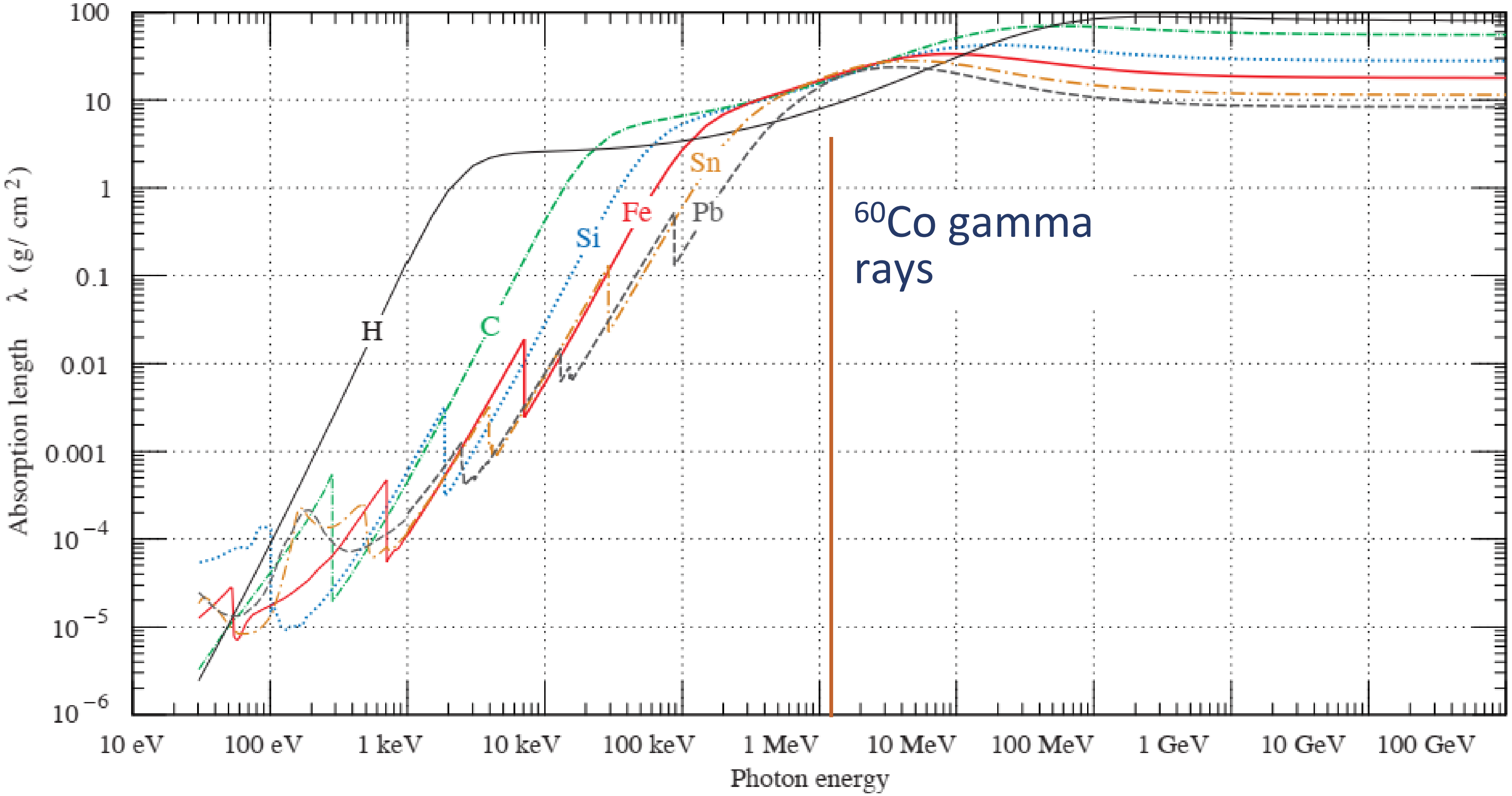
M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)

Photons

λ is the photon "mass attenuation length"

ρ/λ gives you the linear attenuation coefficient μ [cm^{-1}]

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



^{60}Co gamma rays

NIST data: https://physics.nist.gov/PhysRefData/XrayMassCoef/tab3.html

M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)

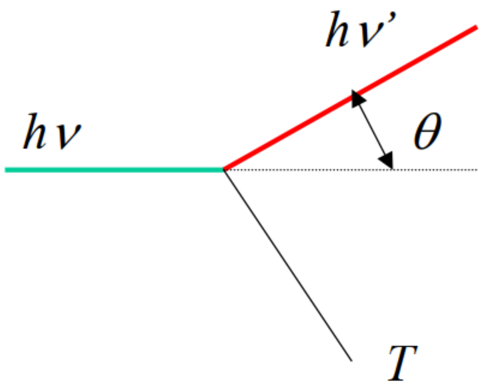
Photons

Dominant interaction around 100 keV to about 10 MeV

- Compton Scattering
  - Scattering of photons by *free* electrons
  - Outgoing photon has lower energy than incoming photon.

$$T = h\nu - h\nu' = h\nu \frac{\gamma(1-\cos(\theta))}{1+\gamma(1-\cos(\theta))}$$

$$\text{where } \gamma = \frac{h\nu}{m_e c^2}$$

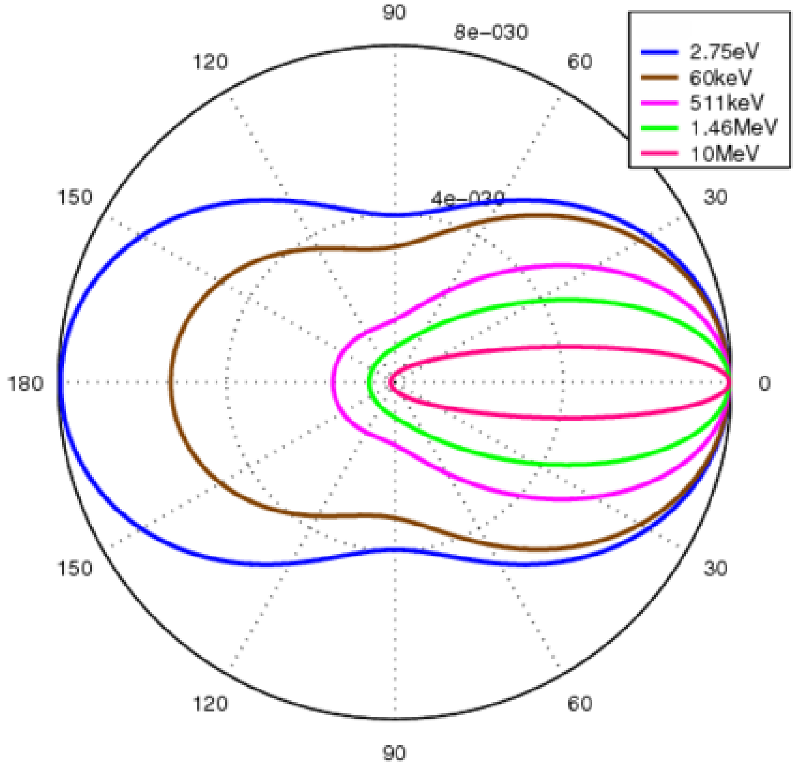


Hobson, Brunel

Photons

Angular distribution is very dependent on the photon energy.

See also animation from Wolfram: https://demonstrations.wolfram.com/KleinNishinaFormulaForComptonEffect/



Photons

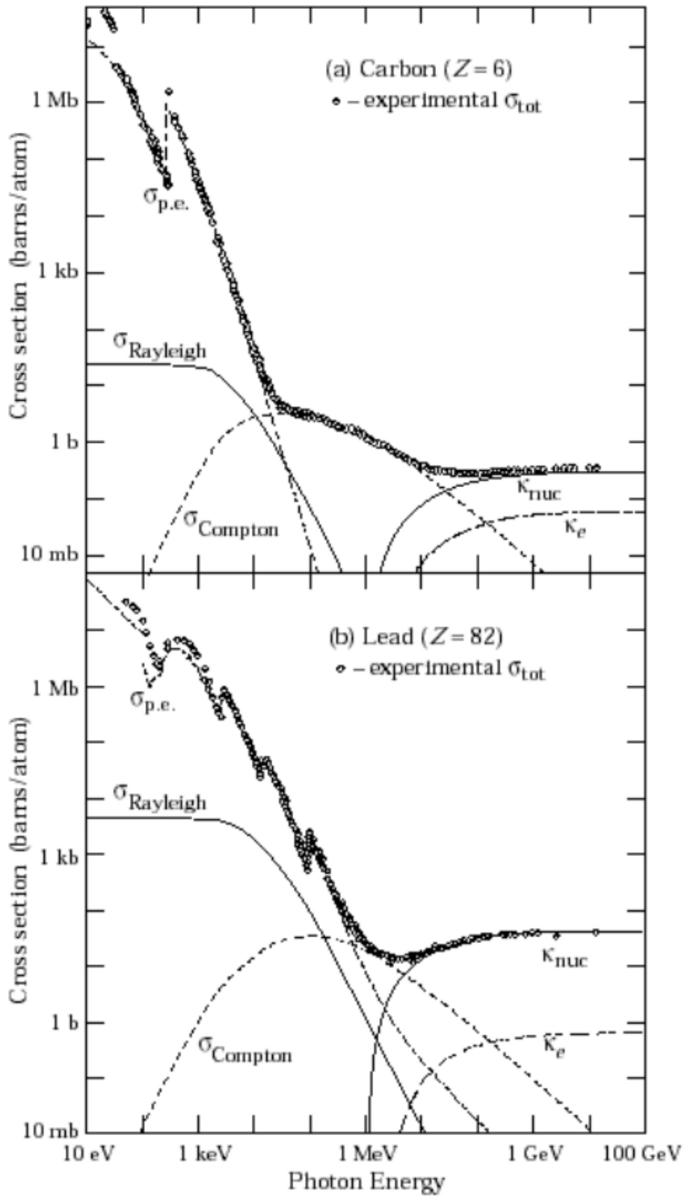
Dominant interaction above 10 MeV

- Pair production
  - Conversion of photon into electron+positron pair
  - Need a third body (momentum conservation), usually this is a nucleus.
  - Threshold energy is 1.022 MeV
  - Mean free path of a gamma ray for pair production is related to the radiation length for electrons:

$$\lambda_{pair} = {}^{9}\!/_{7}\, X_0$$

Photons

Photon absorption cross-sections in Carbon and Lead

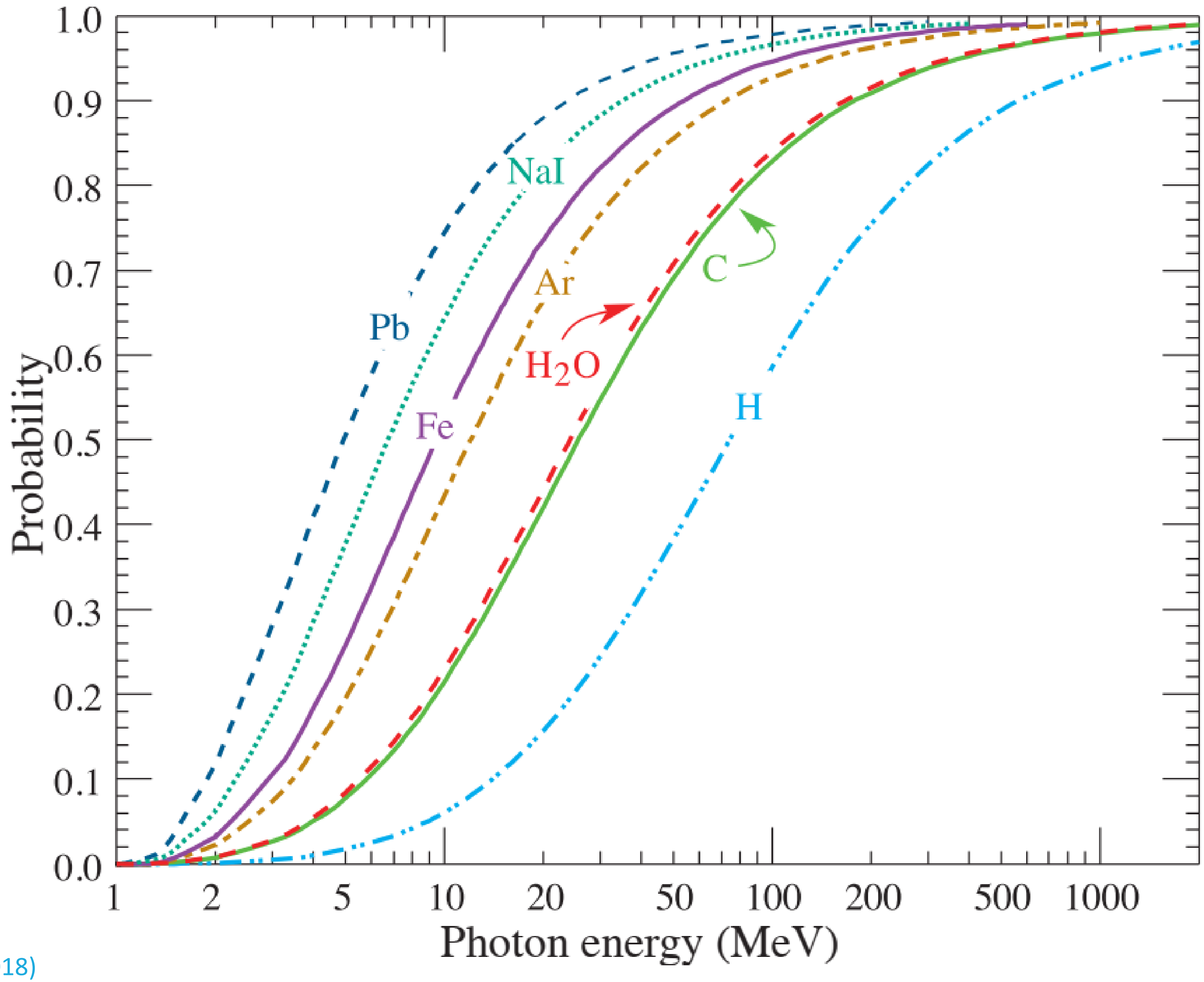


1 barn = 10^{-24} cm^2

M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)

Photons

Probability that a photon interaction will produce an e^+e^- pair



M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)

Scattering of charged particles

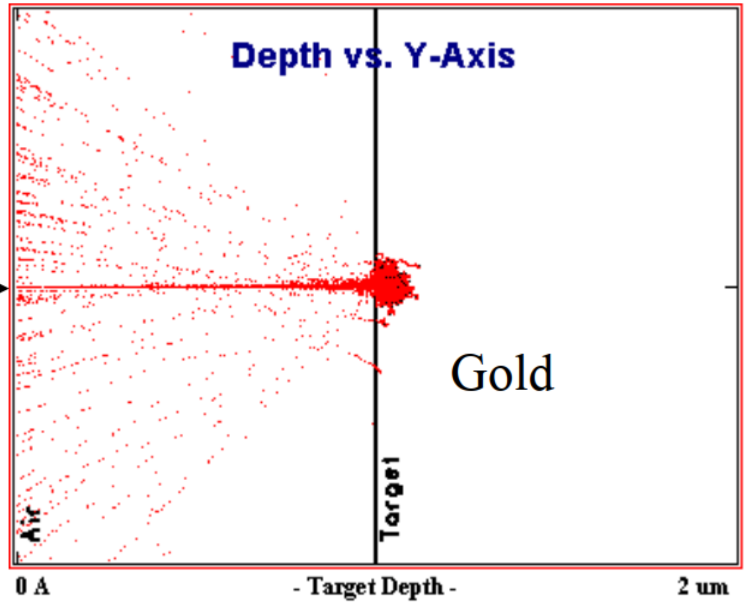
- As well as inelastic collisions with atomic electrons, particles also undergo *elastic* scattering from nuclei
- Classical formula due to Rutherford tells you that the cross-section varies approximately as θ^{-4}
  - Scattering produces mainly very small changes in particle trajectory
  - Cumulative effect of *multiple scattering* is however a net change.
  - For hadrons the strong and Coulomb interactions contribute to the effect.

$$N(\theta) = N_0 \cdot c_F \cdot d_F \frac{Z^2 \cdot e^4}{(8\pi\varepsilon_0 E_\alpha)^2 \cdot \sin^4(\theta/2)}$$

N_0 = number of incident α-particles
c_F = atomic concentration of the foil
d_F = foil thickness
Z = atomic number of the foil
E_α = energy of the α-particles
e = elementary charge
ε_0 = dielectric constant

Scattering of charged particles

Rutherford's Experiment



5 MeV alpha particles incident upon gold foil.

Simulated using the SRIM Monte Carlo

Scattering of charged particles

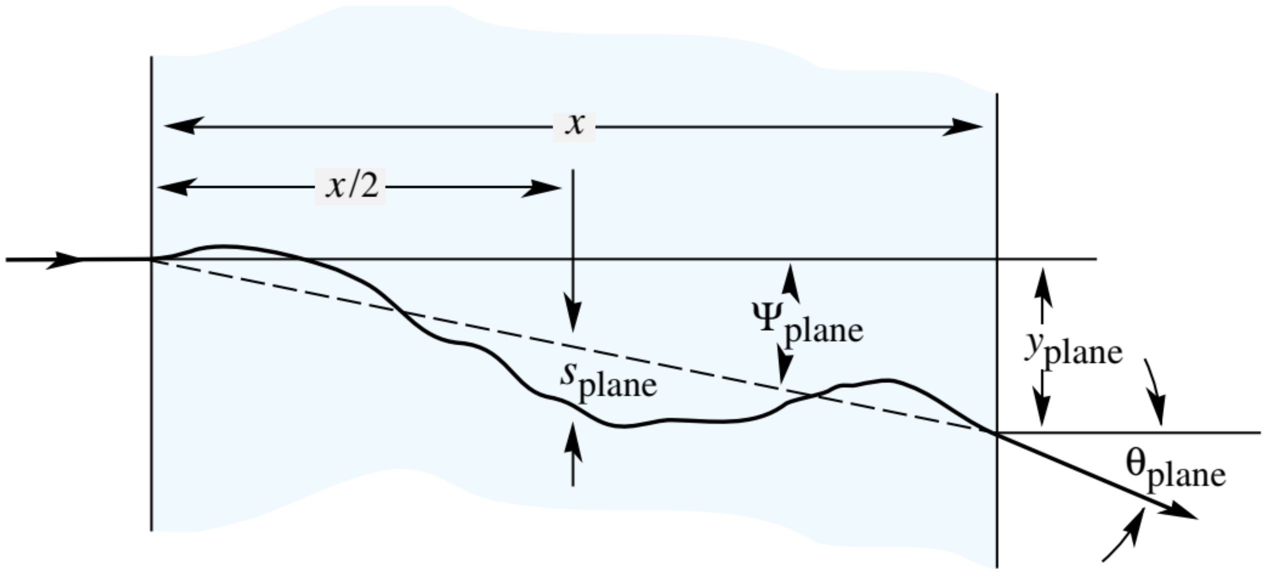


Figure 33.10: Quantities used to describe multiple Coulomb scattering. The particle is incident in the plane of the figure.

If we define

$$\theta_0 = \theta_{\text{plane}}^{\text{rms}} = \frac{1}{\sqrt{2}}\,\theta_{\text{space}}^{\text{rms}} \;, \tag{33.15}$$

then it is sufficient for many applications to use a Gaussian approximation for the central 98% of the projected angular distribution, with an rms width given by Lynch & Dahl [40]:

$$\theta_0 = \frac{13.6\text{ MeV}}{\beta c p}\, z \sqrt{\frac{x}{X_0}} \left[1 + 0.088 \log_{10}\left(\frac{x\, z^2}{X_0 \beta^2}\right)\right]$$

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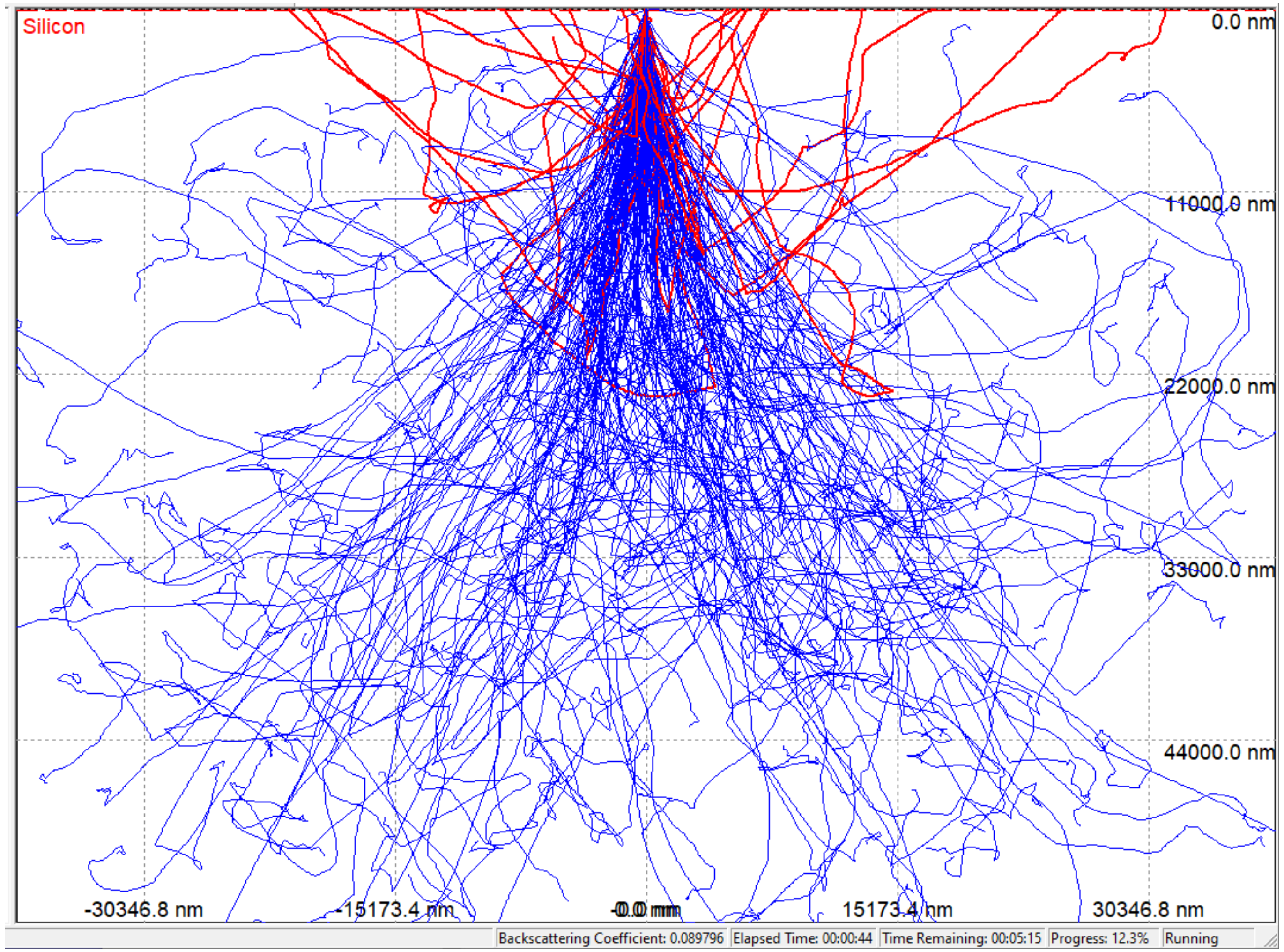
Scattering of charged particles

A collimated beam of 100 keV electrons interacting with silicon. The tracks in red backscatter out of the material.



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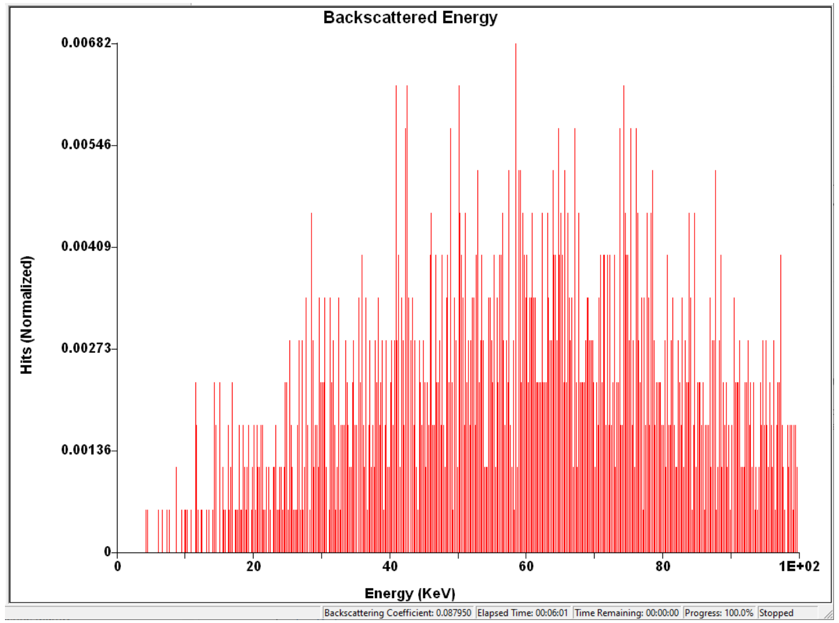
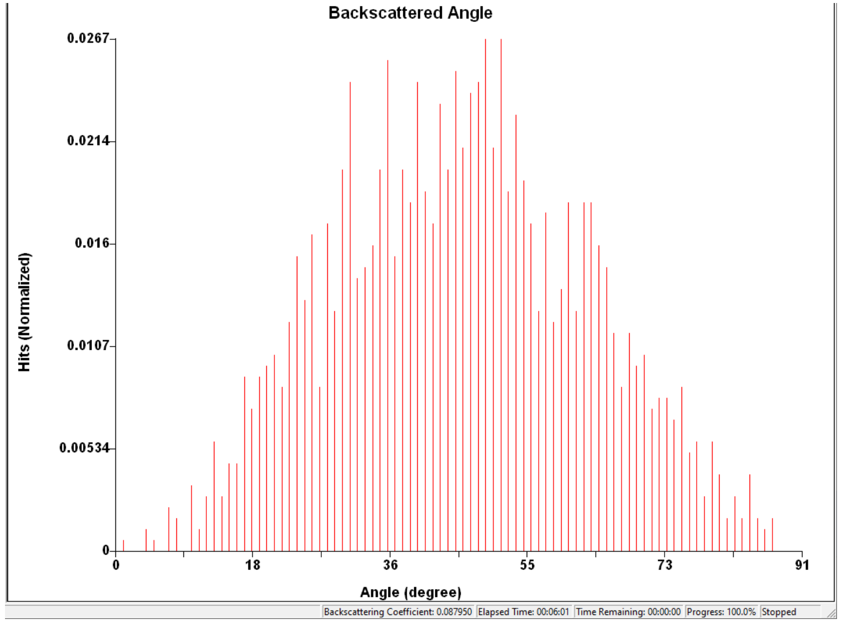
Scattering of charged particles



Backscattering Coefficient: 0.087950 | Elapsed Time: 00:06:01 | Time Remaining: 00:00:00 | Progress: 100.0% | Stopped



Backscattering Coefficient: 0.087950 | Elapsed Time: 00:06:01 | Time Remaining: 00:00:00 | Progress: 100.0% | Stopped

100 keV electrons interacting with silicon. These plots show the backscattered energy and angle of the electrons that leave the material.