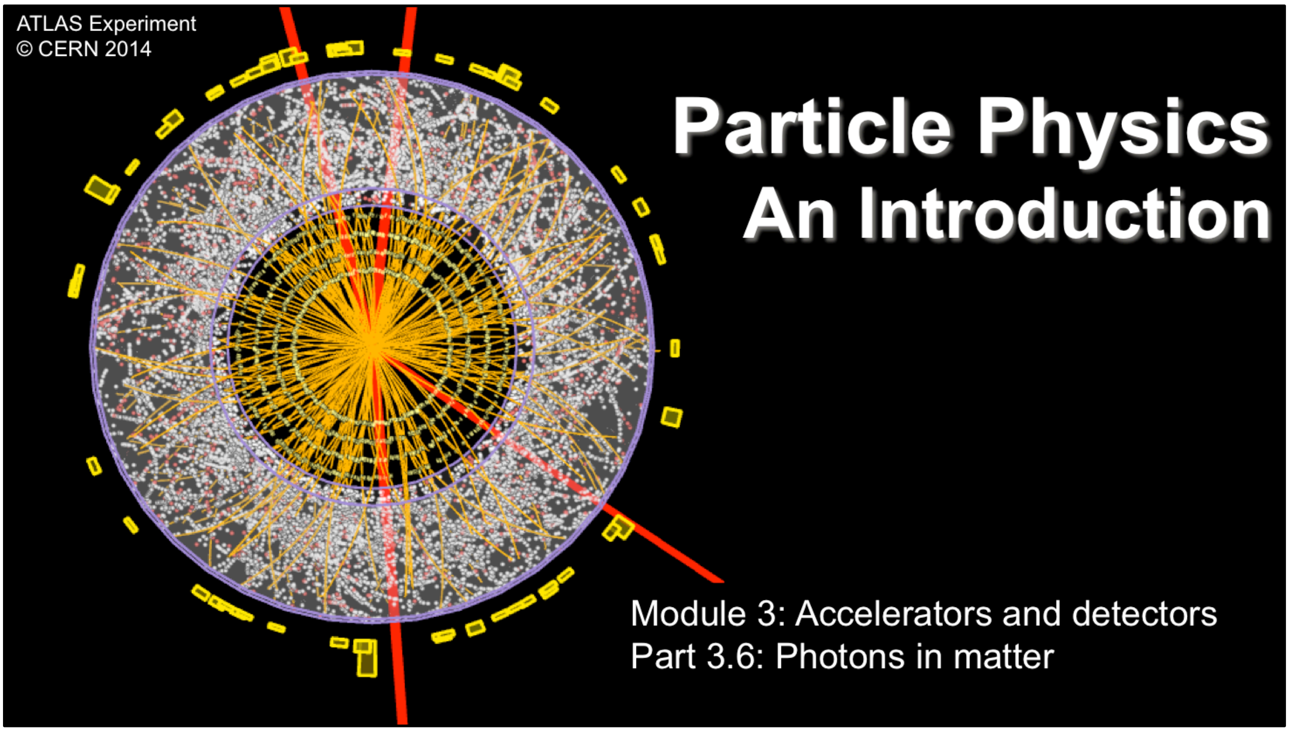


In this module, we will touch the basics of particle acceleration and detection methods.

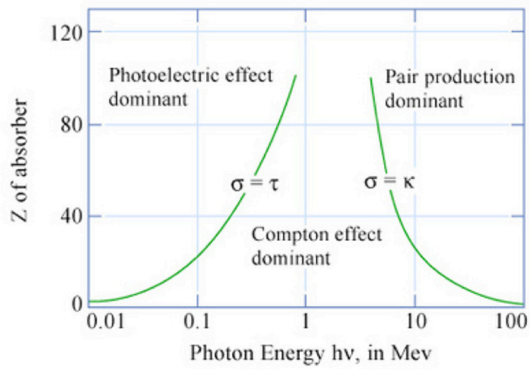
In this video we will demonstrate how photons interact with matter.

At the end of this video you will know the mechanisms by which they are detected:

- The photo-electric effect;
- Compton scattering;
- And pair production.

Photon interactions:

- Photoelectric effect: $\gamma + {}^{A}_{Z}X \rightarrow {}^{A}_{Z}X^{+} + e^{-}$, dominant for $E_I < E_\gamma < 100\,\mathrm{keV}$;
- Compton scattering: $\gamma + e^{-} \rightarrow \gamma + e^{-}$, dominant for E_γ around 1 MeV;
- Pair production: $\gamma + {}^{A}_{Z}X \rightarrow {}^{A}_{Z}X + e^{+}e^{-}$, dominant for $E_\gamma \gg 1\mathrm{MeV}$.



In these processes, the photon is either absorbed or scattered by a wide angle. Most of the photons in a beam keep their original energy but their flux is diminished. A photon beam will thus be **attenuated** rather than lose energy. The probability of an interaction in a given target thickness is a constant proportional to the cross section of the process. This leads to an **exponential decrease of the intensity** of a photon beam as a function of absorber thickness. For an example, see 1.3a video.

Photons are detected by interactions which produce charged particles:

- The photo-electric effect is the absorption of a photon by an atomic electron, dominant for $E_I < E_\gamma <100$ keV;
- Compton scattering is the elastic scattering of a photon off an atomic electron, dominant for E_γ around 1 MeV;
- Pair production is the conversion of a photon into an electron-positron pair in the electromagnetic field of an nucleus, dominant for $E_\gamma >> 1$ MeV.

We will discuss these one by one.

Photoelectric effect:

$$\gamma + {}^{A}_{Z}X \rightarrow {}^{A}_{Z}X^{+} + \mathrm{e}^{-}$$

$$E_e = E_\gamma - E_I$$

ionization energy $E_I = 1$ at 25 eV.

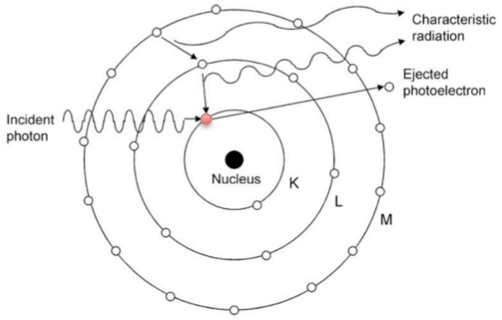
Cross section:

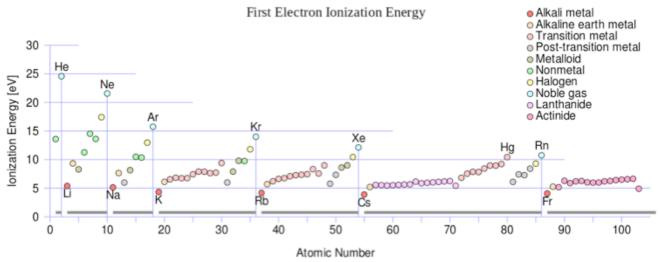
$$\sigma_K \simeq 4\sqrt{2}\alpha^4 Z^5 \left(\frac{m_e}{E_\gamma}\right)^{7/2} \sigma_{Th}$$

$$\sigma_{Th} = \frac{8}{3}\pi r_e^2 = 6.65 \times 10^{-25}\,\mathrm{cm}^2$$

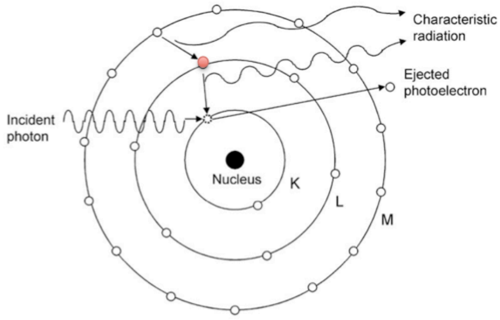
Classical electron radius:

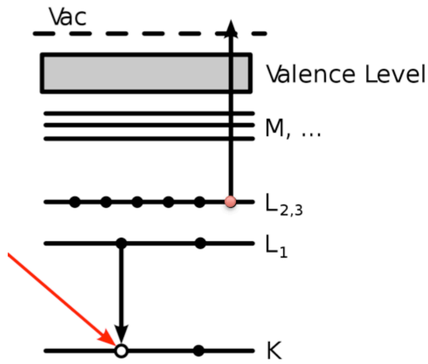
$$r_e = e^2/4\pi m_e \simeq 2.818 \times 10^{-15}\,\mathrm{m}$$





- In the photoelectric process, an atomic electron is released when the atom absorbs the photon. Its kinetic energy is $E_e = E_\gamma - E_I$. The ionization energy E_I depends on the shell where the electron was, and is typically between 1 and 25 eV.
- The photoelectric process is not feasible for a free electron, it would violate conservation of momentum. If $E_\gamma > E_K$, the cross section is dominated at the level of 80% by the absorption of K-shell electrons since the proximity of the nucleus eases the absorption of the recoil energy.
- σ_{Th} is the standard cross section of Thomson scattering. It sets the order of magnitude of the cross section.
- The dependence on Z^5 and $E_\gamma^{-7/2}$ favors the photoelectric process for **low energy photons in heavy materials.**
- At high-energies, i.e. in the relativistic limit, the energy dependence becomes $1/E_\gamma$.





Consequence of a photoelectric absorption:

- emission of an X-ray with energy $E_{L_1} - E_K$;
- emission of an Auger electron, if $E_{L_1} - E_K >$ ionization energy for $L_{2,3}$.

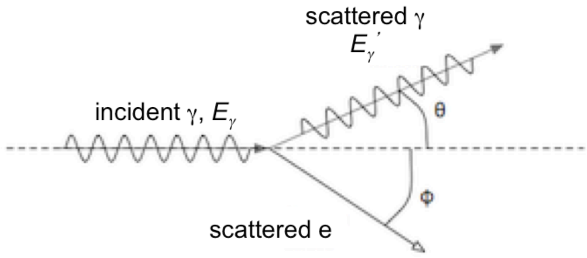
The vacancy opened by the photoelectric effect can be filled by another electron of an upper shell (L, for example) resulting in:

- Either the emission of an **X-ray** with energy $E_L - E_K$;
- Or the emission of an **Auger electron,** if the available energy is greater than the ionization energy for higher shells.

Compton scattering: $\gamma + e^- \rightarrow \gamma + e^-$ ($E_\gamma \gg$ ionization energy)

Klein-Nishima formula:

$$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_e^2 \left(\frac{E'_\gamma}{E_\gamma}\right)^2 \left(\frac{E_\gamma}{E'_\gamma} + \frac{E'_\gamma}{E_\gamma} - \sin^2\theta\right)$$

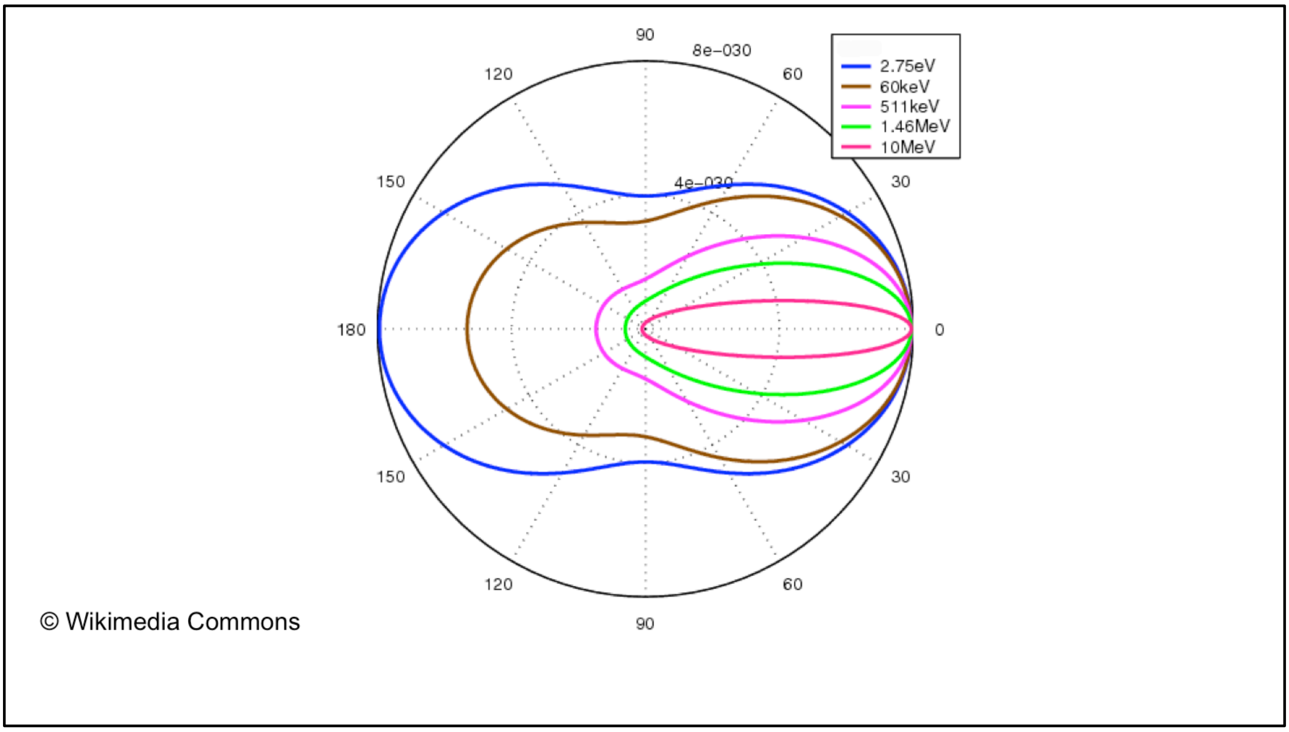


- E_γ, E'_γ: energies of entering and scattered photon
- θ: scattering angle
- Low energy ($E_\gamma \rightarrow 0$): symmetric angular distribution
- High energy ($E_\gamma \gg m_e$): angular distribution peaks at $\theta = 0$.
- $E_{e,max} = E_\gamma/[1 + m_e/(2E_\gamma)]$: maximum electron energy for $\theta = \pi$

http://demonstrations.wolfram.com/KleinNishinaFormulaForComptonEffect/

In **Compton scattering,** dominant around 1 MeV, a photon is scattered off a quasi-free electron. The cross section is given by the Klein-Nishima formula (obtained with QED, see module 4).

The energy of the scattered electron is maximum when θ = 180 °, with $E_{e,max}=E_\gamma/[1+m_e/(2E_\gamma)]$.

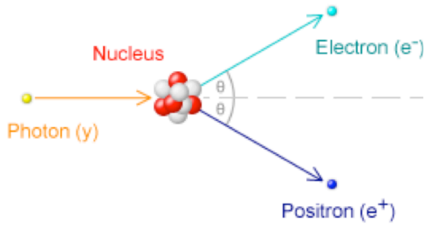


The Compton **cross section** is typically 0.1 barn in the forward direction. For back-scattering, it varies between 0.1 barn at 1 keV and 0.04 barn at 100 keV. At high energy, the process is dominated by the forward scattering.

Photon converted to electron-positron pair:

$$\gamma + {}^{A}_{Z}X \rightarrow {}^{A}_{Z}X + e^{+}e^{-}$$

$$E_{\gamma} \geq 2m_e + 2\frac{m_e}{M_A}$$

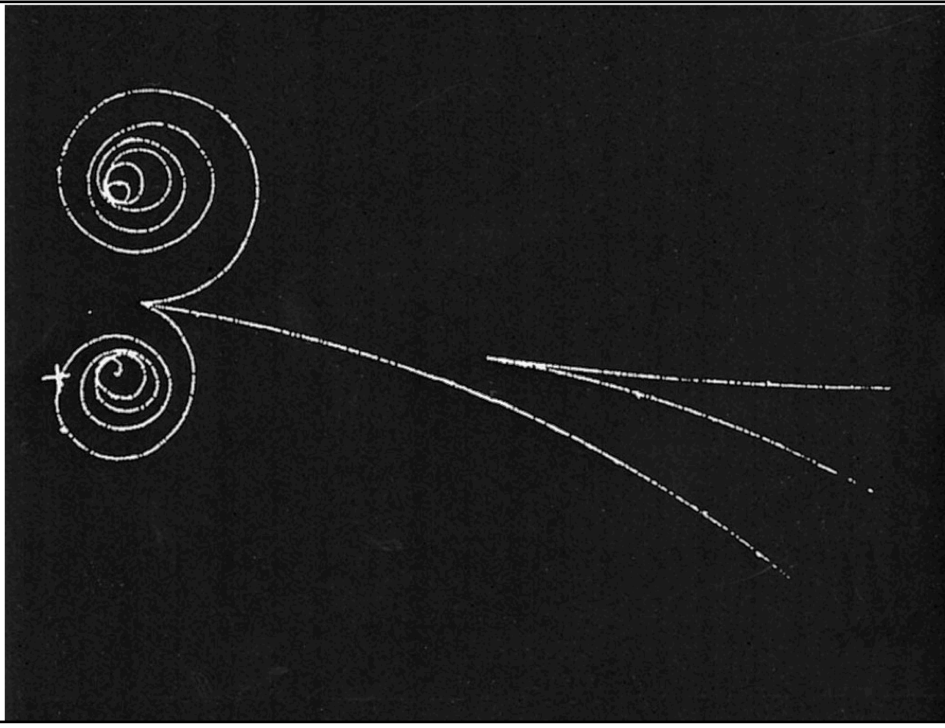


- Requires presence of a recoiling nucleus (recoil energy $\simeq 1$ MeV).
- Cross section per atom at low energy < 1 GeV :

$$\sigma_p \simeq \frac{A}{X_0 N_A}\left[1 - \frac{4}{3}x(1-x)\right]$$

- x: (pair energy)/(photon energy)

- In the electromagnetic field of a nucleus, the photon can convert into an **electron-positron** pair. The energy **threshold** is essentially twice the mass of the electron, with a small correction from the recoil of the nucleus.
- This process can not take place in vacuum because of energy-momentum conservation. But little energy is transmitted to the nucleus, about 1 MeV for heavy nuclei.
- At low and modest energies, the cross section per atom is given in terms of the **radiation length.**
- This is the same length as the one **defined in video 3.5**, i.e. the length after which an electron loses all but *1/e* of its energy by bremsstrahlung.

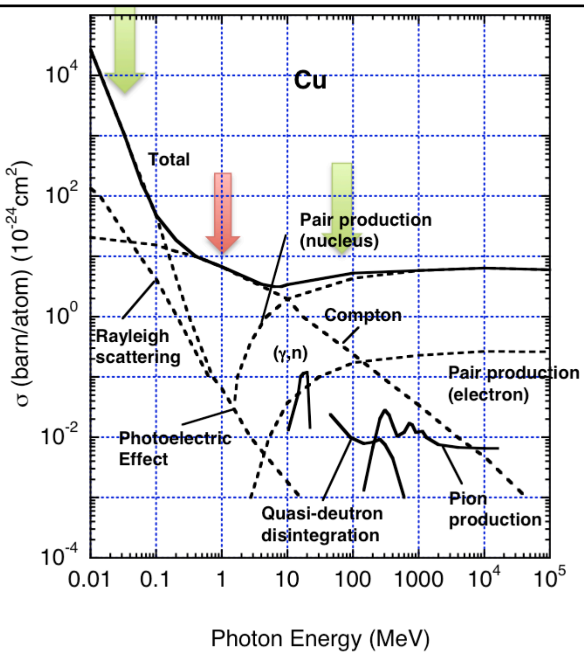


- In this image taken with a **historical bubble chamber** we see the tracks left by charged particles as small bubbles formed in an overheated liquid.
- The chamber is immersed in a magnetic field orthogonal to the projection plane, which deflects the trajectories.
- A photon enters from the left. Here it converts into an electron-positron pair **in the field of an atomic electron** (!), and produces what is called a trident. The pair particles lose energy in the liquid, their trajectories are spirals.
- The atomic electron takes an appreciable recoil energy because of its small mass: it's track goes to the right with little curvature. About halfway, the electron emits a bremsstrahlung photon, which in turn converts into an electron-positron pair, visible by the V-shape tracks on the right.

- Pair production independent of photon energy for $E_\gamma \geq \mathcal{O}(1)$ GeV
- Depends on material via X_0
- Conversion probability per unit distance:

$$w = N_A \frac{\sigma_p}{A} \rho = \frac{7}{9} \frac{\rho}{X_0}$$

- Dominant processes:
  photoelectric effet at low energy,
  pair production at high energy,
  Compton scattering in between

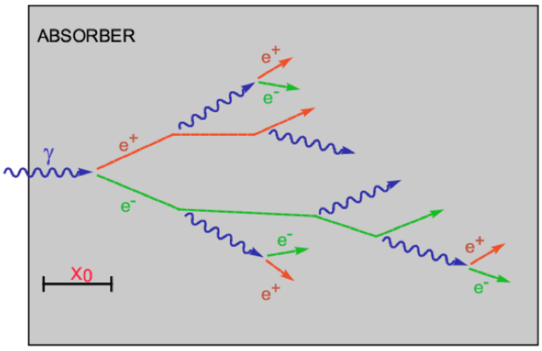


- The cross section for pair production becomes almost **independent of the photon energy** above $E_\gamma \cong 1$ GeV, and depends only on the material, i.e. on X_0.
- The **conversion probability** per unit distance is inversely proportional to the radiation length.
- The **mean free path** for a photon before conversion is the inverse of this probability, and thus $(9/7)X_0$.

- The busy plot on the right shows a summary of the contribution of all processes to the photon cross section in matter.
- Among all these, the most important are the **photoelectric effect** at low energies and **pair production** at high energies.
- In between, around 1 MeV, at the minimum of the cross section, **Compton scattering** dominates.

Dominant processes for $E \geq 1$ GeV :

- Electrons lose energy by bremsstrahlung
- Photons convert through pair production
- Characteristic length : X_0
- Successive combination: electromagnetic shower



- At high energy, $E_\gamma > 1$ GeV, **electrons and positrons** lose their energy almost exclusively by bremsstrahlung.
- **Photons** convert to electrons and positrons by **pair production**.
- The two phenomena have the **same characteristic length,** the radiation length.
- The successive combination of these two effects results in the formation of an **electromagnetic shower,** whenever an electron, positron or photon enters a medium.

In the **next video** we see how ionization detectors measure the passage of charged particles.