Interactions of particles with matter

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Particle Physics (2015/2016)

LIP

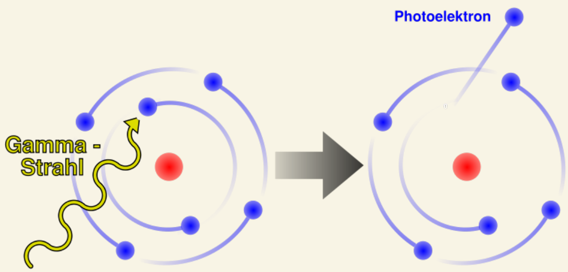
TÉCNICO LISBOA

Interaction of photons with matter

Photon interaction with matter

Photons interact with matter, producing charged particles, through the following process: **Photoelectric effect**

Photoelectric effect



The photon is absorbed by an atom that ejects an electron

$$T = E_\gamma - E_b$$

Photon interaction with matter

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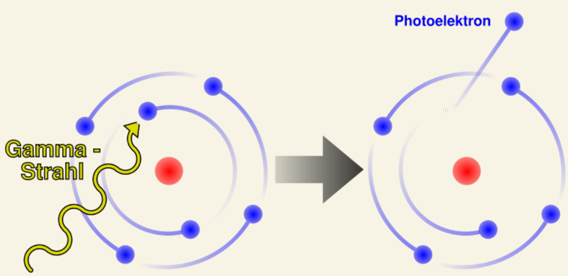
Photoelectric effect



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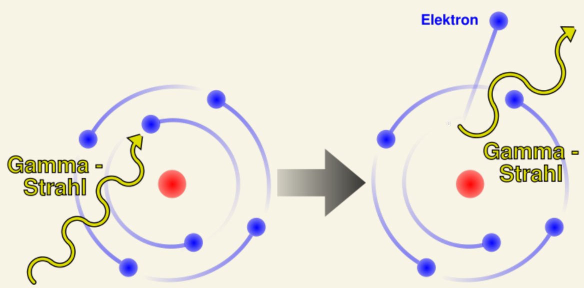
Compton scattering

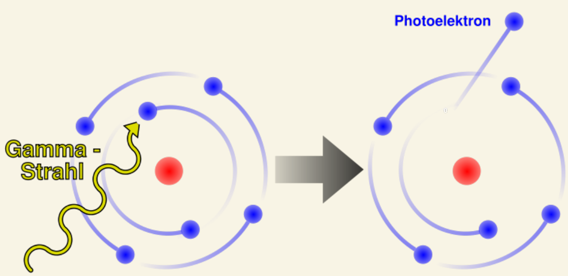


The photon hits a nearly free electron ejecting it

Photon interaction with matter

Photons interact with matter, producing charged particles, through the following processes: **Photoelectric effect, Compton scattering, Pair Production**

Photoelectric effect



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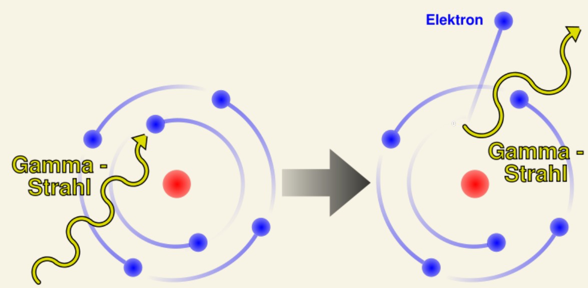
Compton scattering



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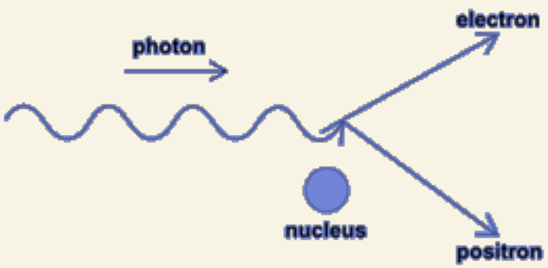
Pair production



The photon converts into a electron-positron pair near the field of the nucleus

$$E_\gamma \geq 2m_e c^2 \approx 1.022\,\mathrm{MeV}$$

Photon cross section with matter

Photoelectric effect:

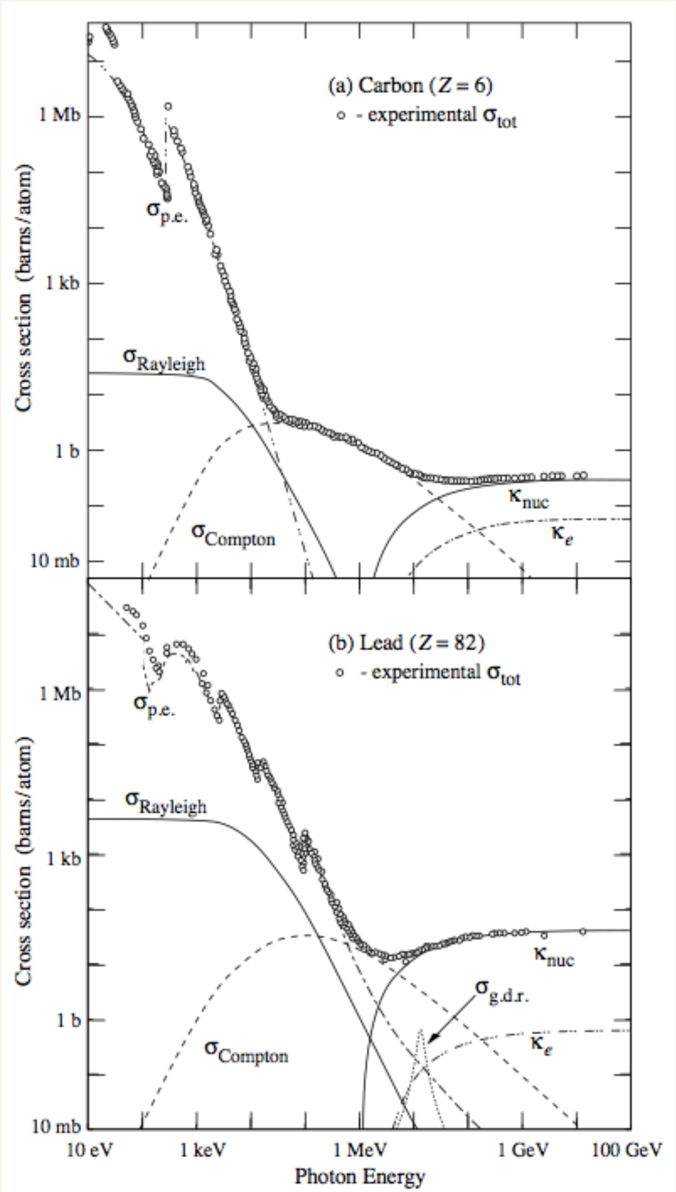
$$\sigma \sim Z^5 \left(\frac{m_e c^2}{E_\gamma}\right)^3$$

Compton Scattering:

$$\sigma_C \sim \pi r_e^2 \frac{m_e c^2}{E_\gamma}\left[\frac{1}{2} + \ln\left(\frac{2m_e c^2}{E_\gamma}\right)\right]$$

Pair Production:

$$\sigma_{pair} \sim 4\alpha Z^2 r_e^2 \left[\frac{7}{9}\ln\left(\frac{183}{Z^{1/3}}\right)\right] \sim \frac{7}{9}\frac{A}{N_A}\frac{1}{X_0}$$



Absorption of photons in matter

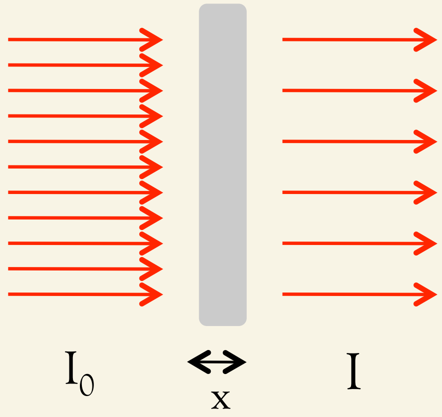
The total cross section for a photon that interacts with an atom is given by:

$$\sigma_\gamma^{tot} = \sigma_{pe} + Z\sigma_C + \sigma_{pair}$$

Probability of interaction per length unit of traversed matter
(linear attenuation coefficient) :

$$\mu \equiv p_\gamma = N_A \frac{\rho}{A} \sigma_\gamma^{tot}$$

Photon beam attenuation



$$I_\gamma(x) = I_0\, e^{-\mu x}$$

Absorption length: $\lambda_{abs} = 1/\mu$

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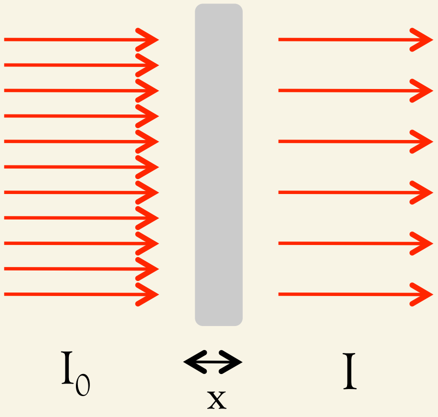


$$I_\gamma(x) = I_0\, e^{-\mu x}$$

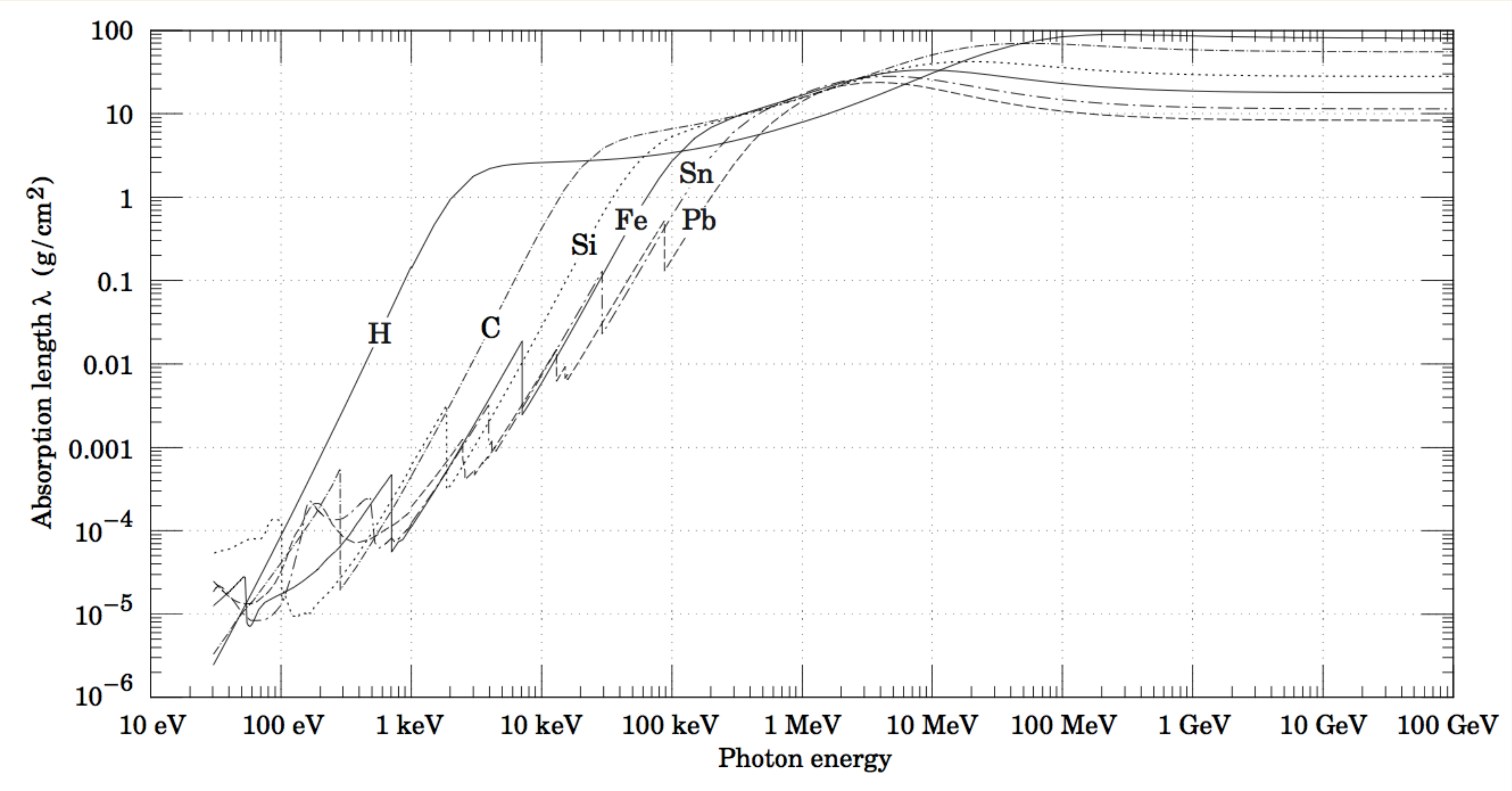
Absorption length: $\lambda_{abs} = 1/\mu$

To make this quantities less dependent of the materials involved it is usual to divide/multiply it by the density:

- μ / ρ [g^{-1} cm^2] (mass attenuation coefficient)
- $\lambda . \rho$ [g cm^{-2}]

Absorption of photons in matter

- Depends on the material and on the photon energy



Interaction of charged particles with matter

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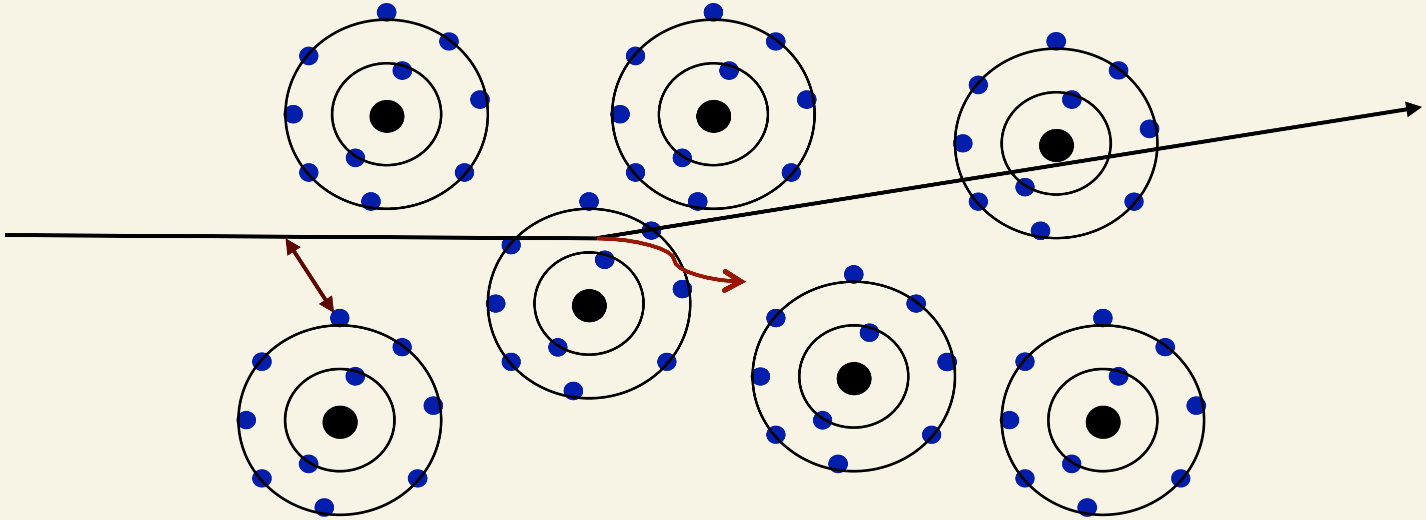


- Interaction with atomic electrons:
  - the incident particle collides inelastically losing its energy and the atoms suffer excitation or ionization
- Interaction with the nucleus:
  - the incident particle is deflected by the nucleus electric field, undergoing elastic interactions (multiple scattering).
  - the particle is accelerated and radiates Bremsstrahlung photons

dE/dX: Bethe-Block Formula

- Energy loss of a charged particles through inelastic collisions:

$$-\frac{1}{\rho}\frac{dE}{dx} = 2\pi N_A r_e^2 m_e c^2 \frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\left(\frac{2m_e\gamma^2 v^2 T_{max}}{I^2}\right) - 2\beta^2 - \delta\right]$$

$$2\pi N_A r_e^2 m_e c^2 = 0.1535\,\mathrm{MeV\,cm^2\,g^{-1}}$$

r_e Classic electron radius ($r_e = 2.817 \times 10^{-13}$ cm)

$$r_e = \frac{e^2}{4\,\pi\,\varepsilon_0\,m_e c^2}$$

m_e Electron mass ($m_e = 0.511$ MeV/c^2)

N_A Avogadro number ($N_a = 6.023 \times 10^{23}$ mol^{-1})

ρ Density of the traversed medium

z Incident particle charge

Z Medium atomic number

A Medium mass number

I Average excitation energy

$$\frac{I}{Z} = \begin{cases} 12 + \frac{7}{Z}\ [eV] & (Z<13) \\ 9.76 + 58.8Z^{-1.19}\ [eV] & (Z>=13) \end{cases}$$

β Incident particle velocity ($\beta = \frac{v}{c}$)

γ Lorentz factor ($\gamma^{-1} = \sqrt{1-\beta^2}$)

δ Density correction factor

T_{max} Maximum energy transferred in the collision

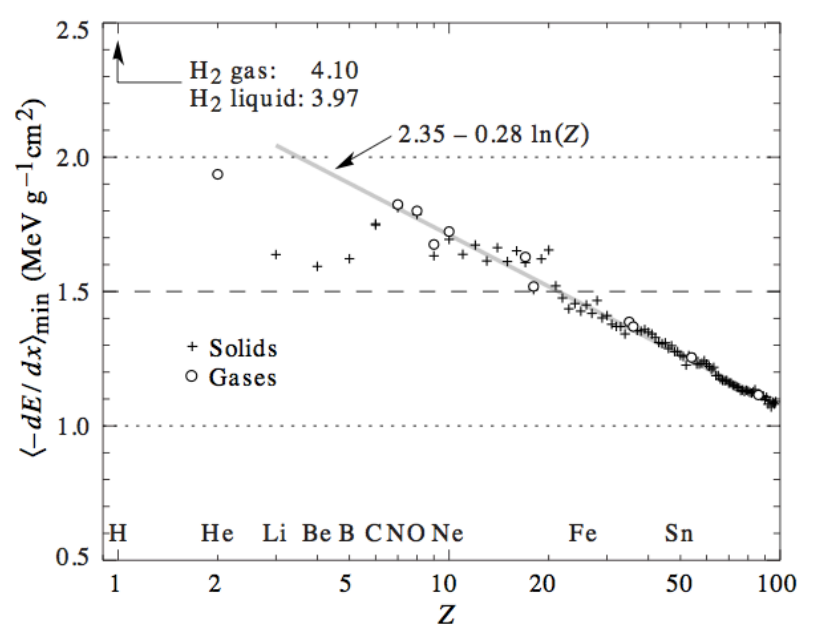
$$T_{max} \sim 2\,m_e c^2\,\beta^2\,\gamma^2 \quad (M >> m_e)$$

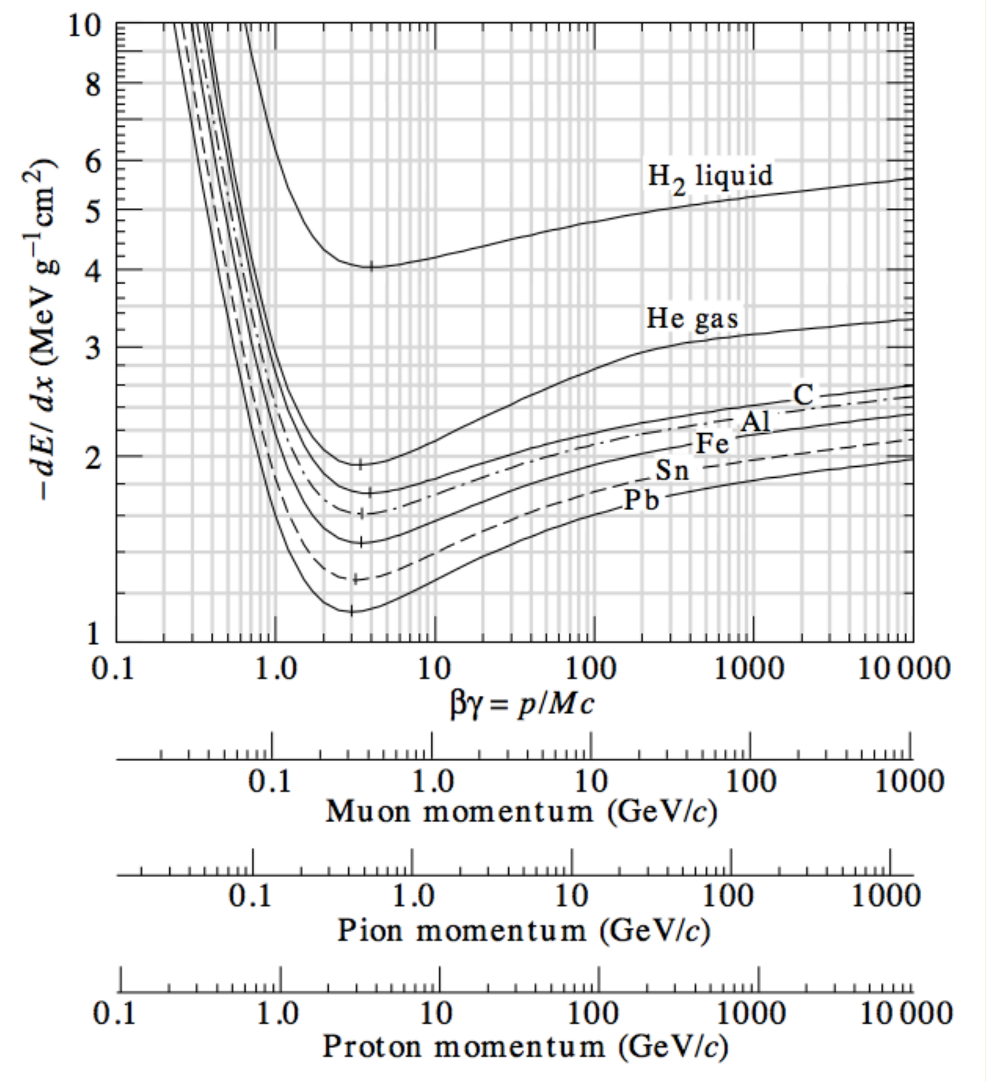
dE/dX: Energy loss

- The energy loss depends of the incident particle velocity
- The minimal energy loss occurs when $\beta\ \gamma \approx 3.5$

(minimum ionizing particle - MIP)

$$\left.\frac{dE}{dx}\right|_{min} \sim 2\,\mathrm{MeV\,cm^2\,g^{-1}}$$



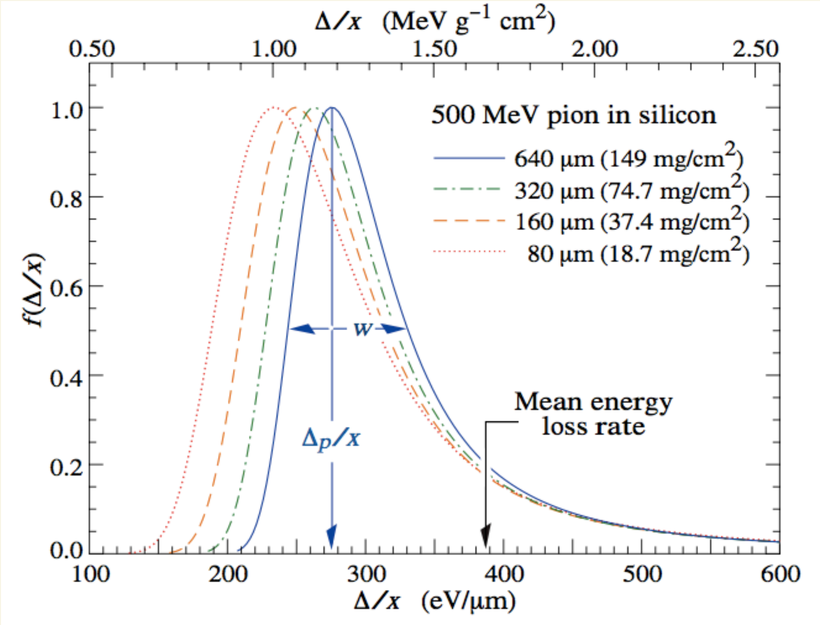


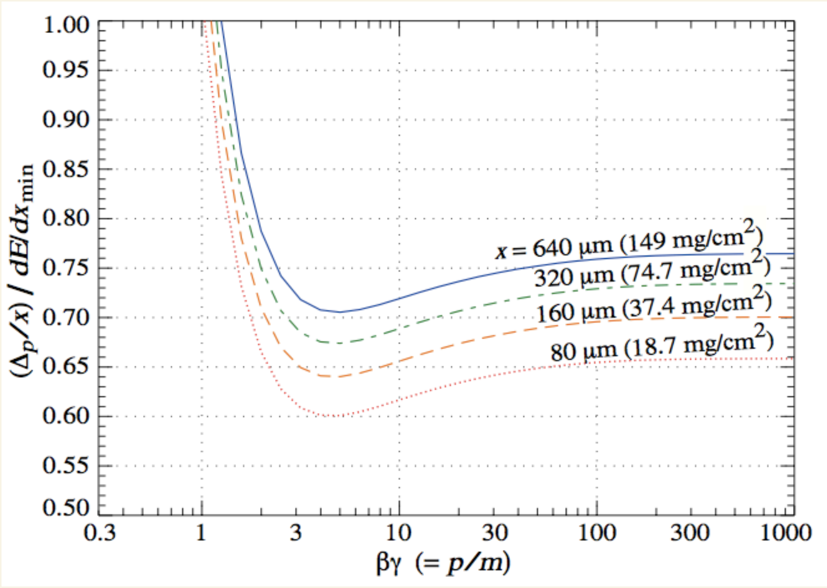
dE/dX: Energy loss fluctuations

- The energy loss of a single particle fluctuates due to the stocasthic nature of the involved processes
- Energy loss for a single particle usually described by the so-called Landau distribution

$$p(x) = \frac{1}{\pi}\int_0^\infty e^{-t\log t - xt}\sin(\pi t)dt$$

- Distribution has a long tail
  - Production of δ-rays, i.e., knock-out electrons
    - E >> ionization potential





Bremsstrahlung radiation

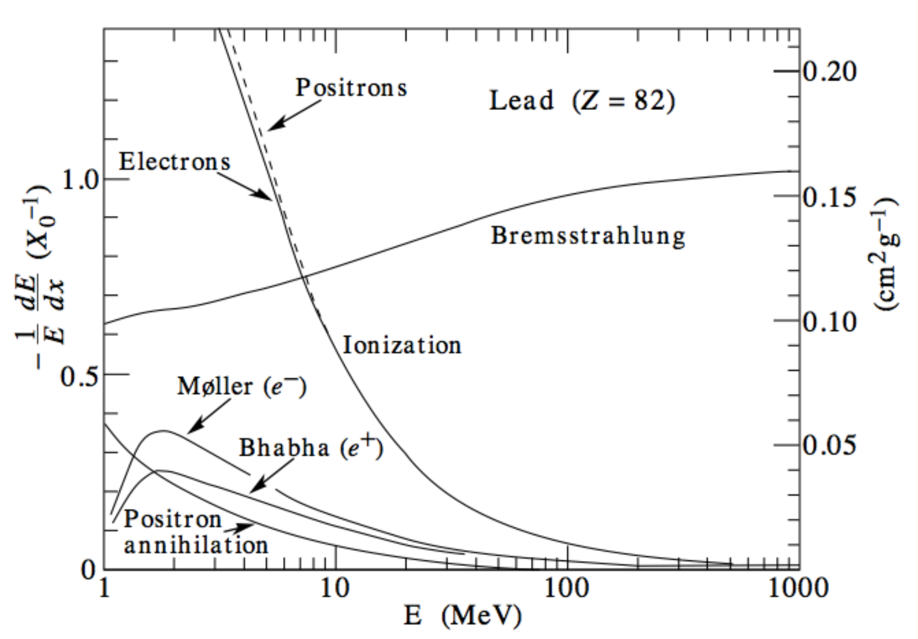
- Charged particles radiate when accelerated
- Acceleration caused by the nucleus field

$$\left(\frac{dE}{dx}\right)_{rad} \sim \frac{N_A}{A}\frac{4Z(Z+1)\alpha^3(\hbar c)^2}{m^2c^4}E\ln\left(\frac{138}{Z^{1/3}}\right)$$

- Energy loss proportional to:
  - Inverse of the square mass
  - Incident particle energy

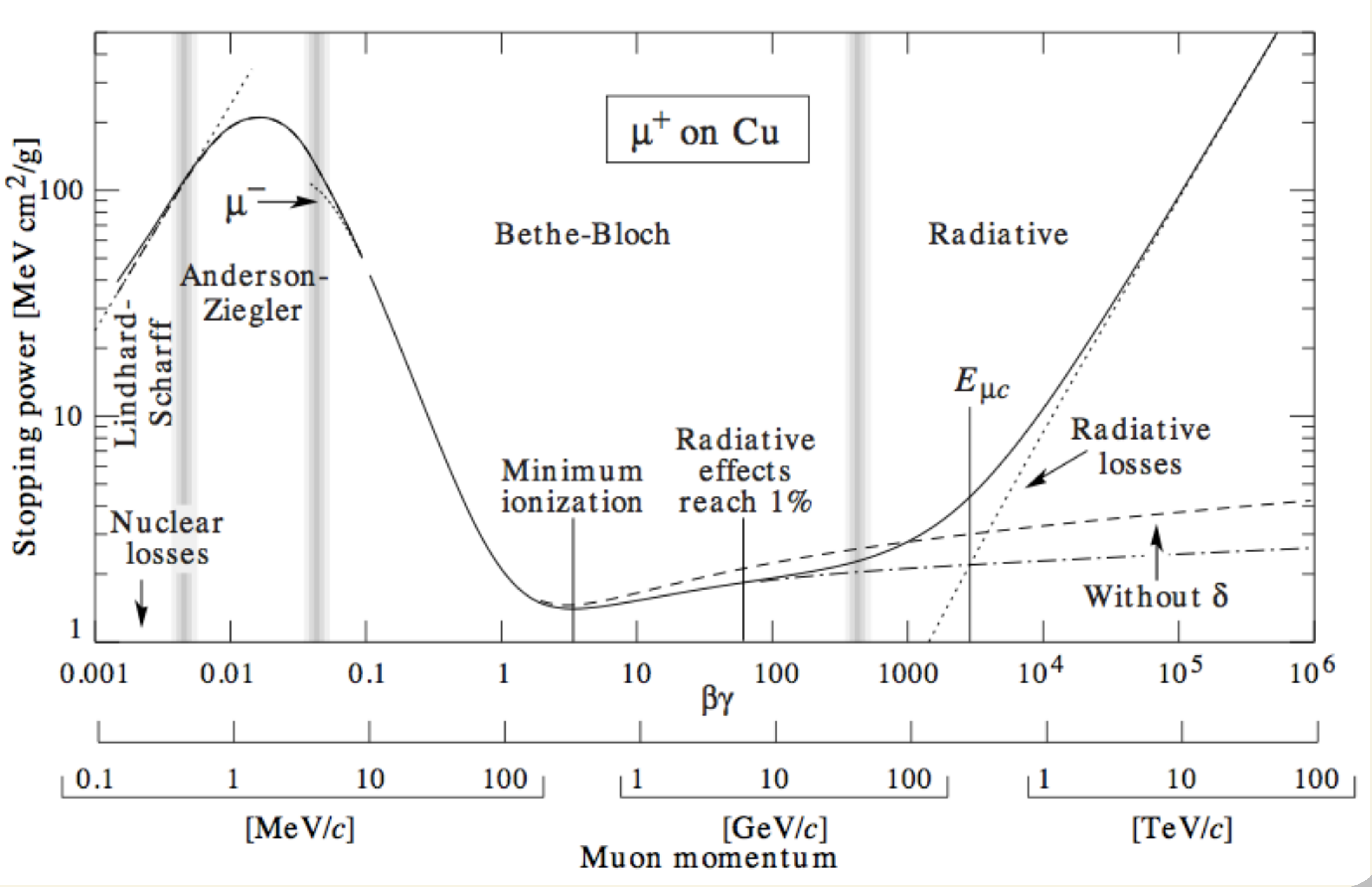
$$\left(\frac{dE}{dx}\right)_{rad} = \frac{E}{X_0}$$

  - X_0: radiation length
    - depends of the medium
  - Critical energy:



$$\left(\frac{dE}{dx}\right)_{ion} \sim \left(\frac{dE}{dx}\right)_{rad} \qquad E_{crit} \sim 10 - 100\ \mathrm{MeV}$$

dE/dX: Charged particles energy loss

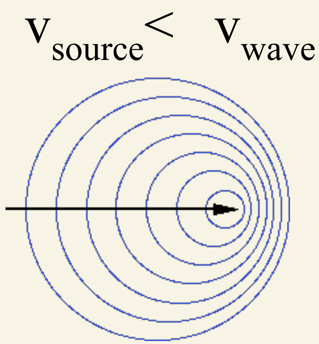


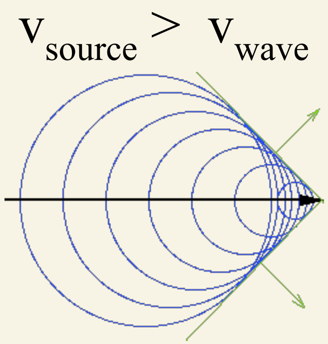
Cerenkov radiation

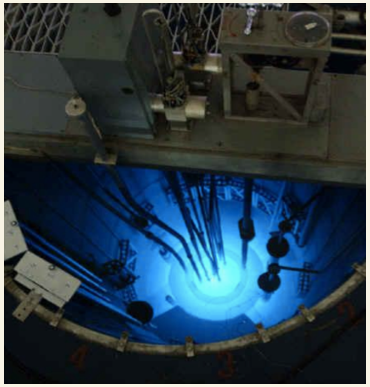
- When a charged particle travels at a velocity greater than the velocity of the light in that medium

$$v_c = \frac{c}{n}$$

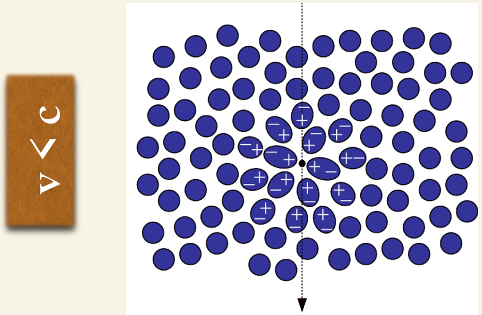
- There is a coherent emission of photons designated Cerenkov radiation

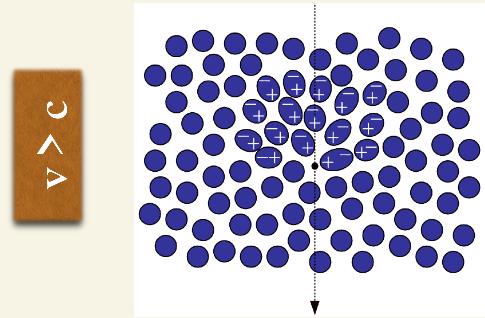




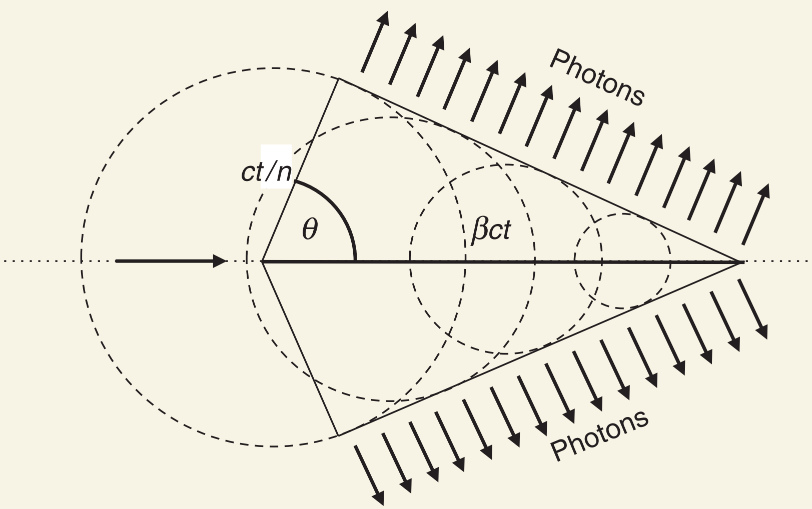


Cerenkov radiation



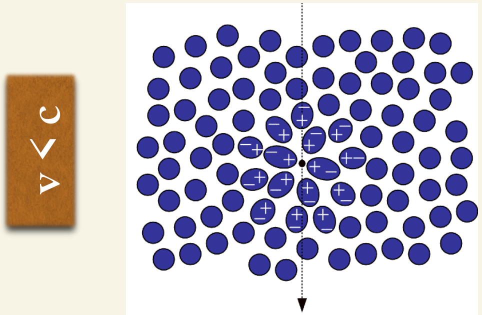


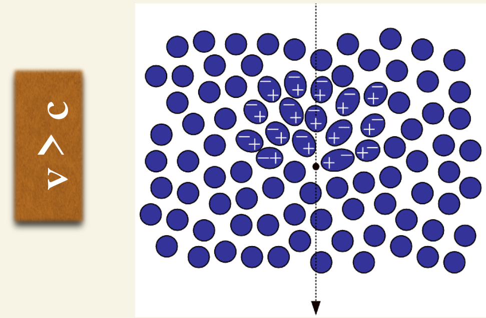
- Cerenkov photons are emitted at an angle:



$$\cos\theta_c = \frac{1}{\beta n}$$

Cerenkov radiation





- Number of Cerenkov photons:

$$\frac{d^2N}{dE\,dx} = \frac{\alpha^2 z^2}{r_e m_e c^2}\sin^2\theta_c$$

$$= \frac{\alpha^2 z^2}{r_e m_e c^2}\left(1 - \frac{1}{\beta^2 n^2}\right)$$

$$\simeq 370\, z^2 \sin^2\theta_c(E) \quad [eV^{-1}cm^{-1}]$$

α : **fine structure constant**

Reflects the strength of the electromagnetic force

$$\alpha = \frac{e^2}{4\pi\varepsilon_0 hc} = \frac{1}{137}$$

Cerenkov radiation

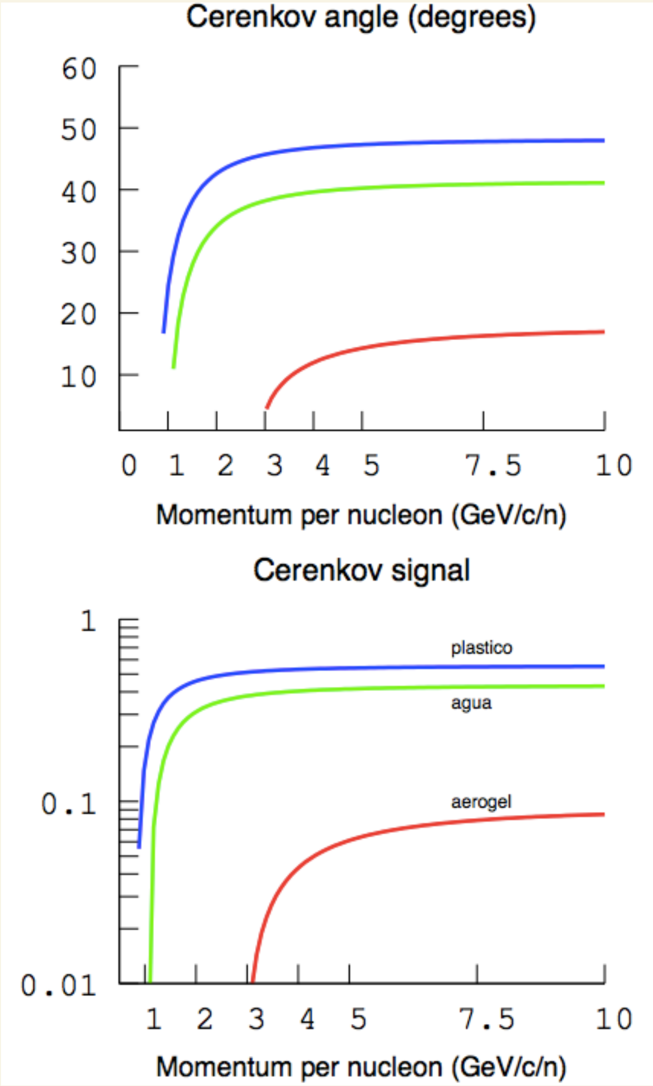
- Number of emitted photons:

$$N_\gamma \simeq z^2 370\, L \int_E \varepsilon(E) \left(1 - \frac{1}{\beta^2 n(E)^2}\right) dE$$

- Cerenkov photon energy spectrum:

$$\frac{dN}{dE} \simeq cte \Rightarrow \frac{dN}{d\lambda} = \frac{dN}{dE}\frac{dE}{d\lambda} \Rightarrow \frac{dN}{d\lambda} \propto \frac{hc}{\lambda^2}$$

- At high energy the signal and emission angle of the Cerenkov radiation depends essentially of the properties of the traversed material

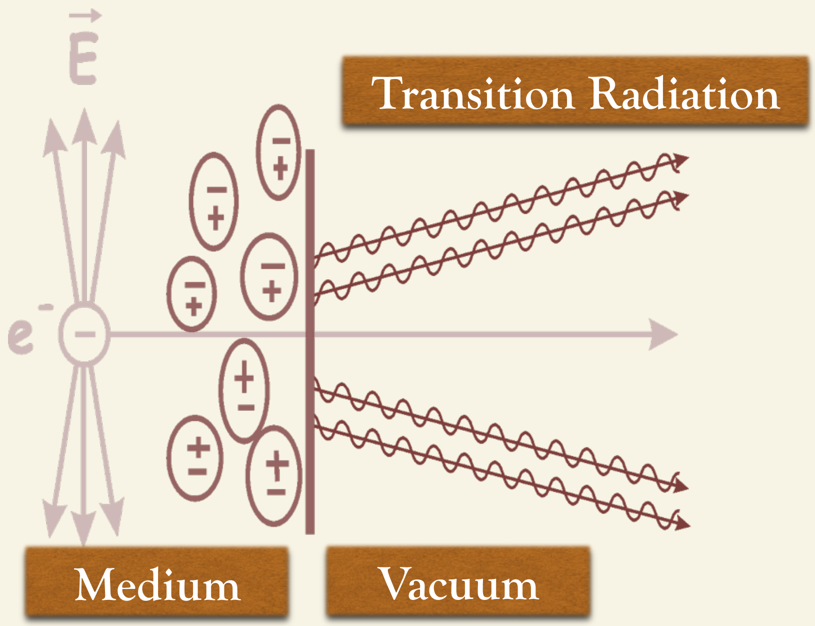


Transition Radiation

- Electromagnetic radiation produced when relativistic charge particle cross different dielectric mediums
- Related with the polarizations of the medium
  - Depends on the plasma frequency in the material
- The average number of photons produced is:

$$N_\gamma \approx 0.8\alpha Z^2 \approx 5.9 \times 10^{-3} Z^2$$

- Radiation produced is proportional to square of the particle charge



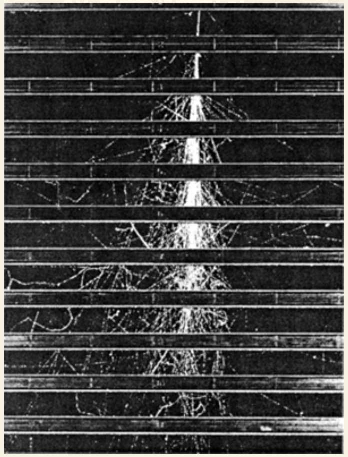
Very high energy phenomena

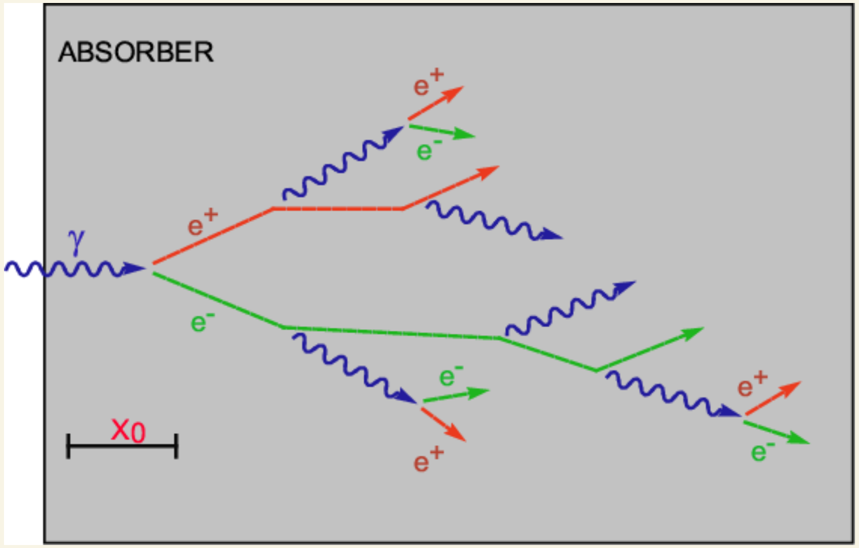
Electromagnetic cascades

- An incident gamma (very energetic photon) in an absorber (material usually dense) originates an electromagnetic cascade:
  - Bremsstrahlung
    - "braking radiation"
    - Particles accelerated in a nucleus field will radiate
  - Pair production
  - Pair annihilation
  - The particle multiplication

occurs until:

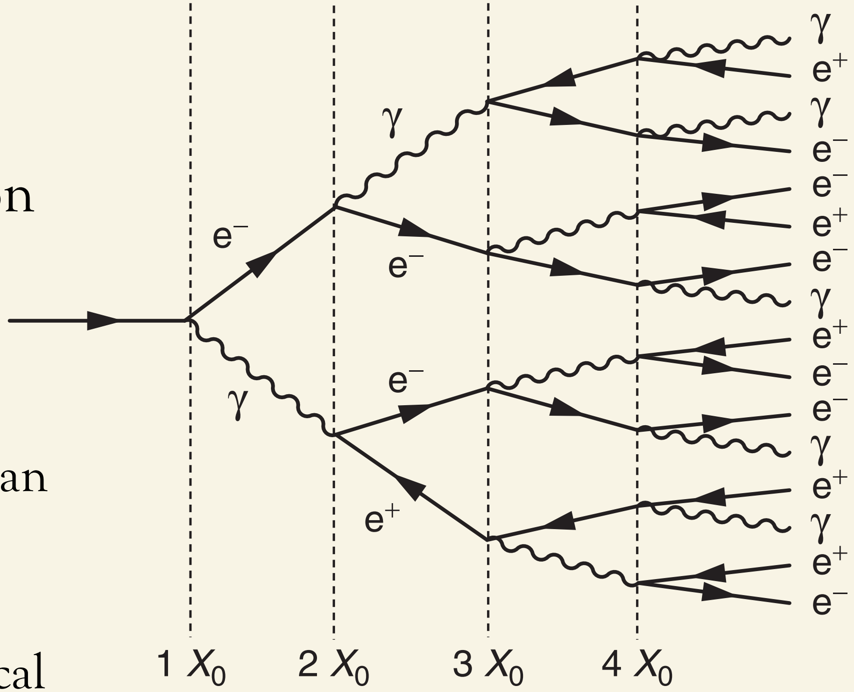
- $E_{e^\pm} < E_c$
- $E_\gamma < 2m_e c^2$





Electromagnetic cascades

- The development of an electromagnetic shower is a stochastic process
  - Monte Carlo simulation
- Analytical treatment approximation
  - Heitler model
    - Knowing that for high-energy photon the radiation length is approximately 7/9 of of the mean free path of the e+e— pair-production
    - Multiplication stops when critical energy is reached

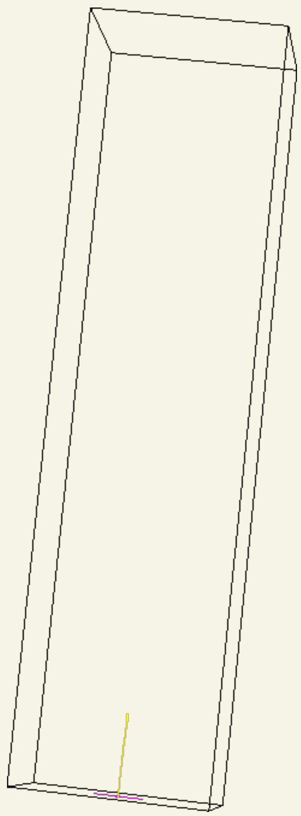


$$\Rightarrow X_{max} \propto \ln(E/E_c)$$

Electromagnetic showers

- Monte Carlo simulation of a high energy electron that enters a crystal cintilator

2 GeV



- Particles of low energy transfer their energy to the material through:
  - Ionization/Excitation (charged particles)
  - Photoelectric effect / Compton scattering (photons)

Electromagnetic showers

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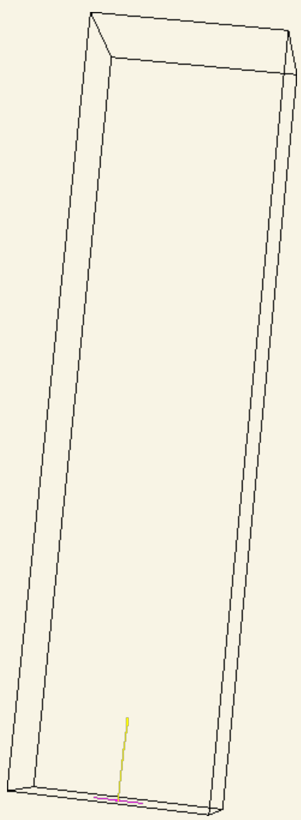
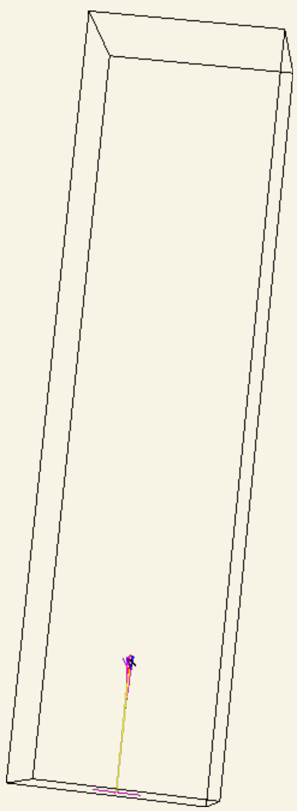


80 GeV



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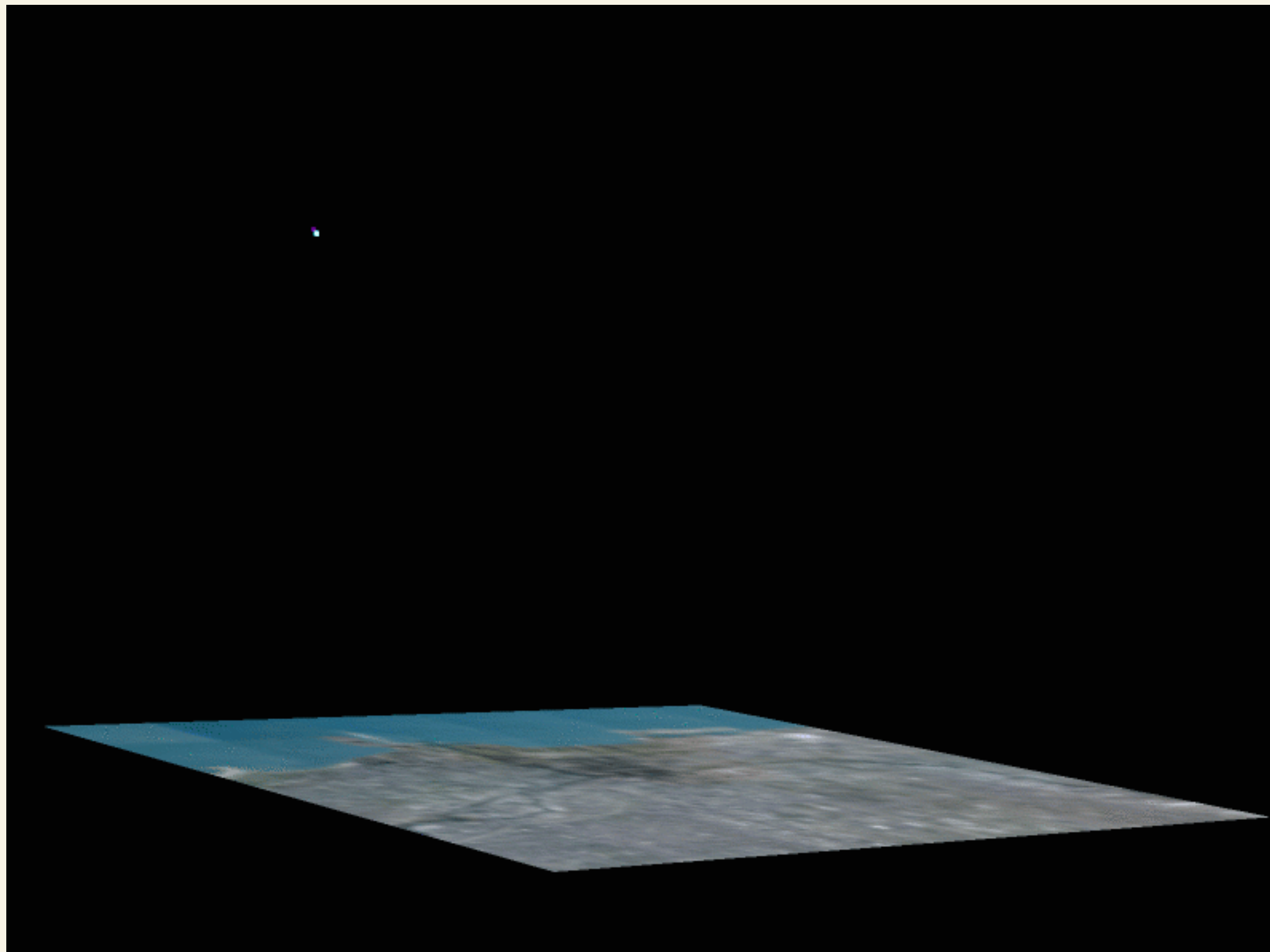
Extensive Air Showers

- Atmospheric cascades initiated by high energy cosmic rays
  - (E = [10^{15};10^{20}] eV)

Simulation of a cascade induced by a gamma of 200 GeV

The cascade began at an altitude of 5 km

Particles of hadronic nature also produce extensive air showers



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  - Chapter 1, section 1.2 and 1.3
- Particle Data Group
  - Passage of particles through matter (review)
    - http://pdg.lbl.gov/2014/reviews/rpp2014-rev-passage-particles-matter.pdf
- A. De Angelis, M. Pimenta, Introduction to particle and astroparticle physics
  - Chapter 4, section 4.1

Problems

① Consider the interaction of 2 photons converting into pair ($e^- e^+$). Assuming that one of the photons has an energy of E_1=1MeV what is the minimal energy of the other photon in order to allow the process?

② A photon can convert into a pair when in the presence of a nucleus. What is the role of the nucleus?

③ Consider a proton of 1 GeV/c traversing a gas. The refraction index depends on the gas pressure.

a. Determine the minimum refraction index so that the proton emits Cerenkov radiation.
b. If the refraction index is 1.6 what is the emission angle of the Cerenkov radiation?