JÜLICH
FORSCHUNGSZENTRUM

Lecture B2

INTERACTION of RADIATION with MATTER

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“Autumn Lectures” – Nuclear and Medical Physics

Tbilisi, Georgian Technical University (GTU)

October 16, 2013

OVERVIEW

SCATTERING

PHOTO EFFECT

COMPTON EFFECT

PAIR PRODUCTION

ATTENUATION

BREMSSTRAHLUNG

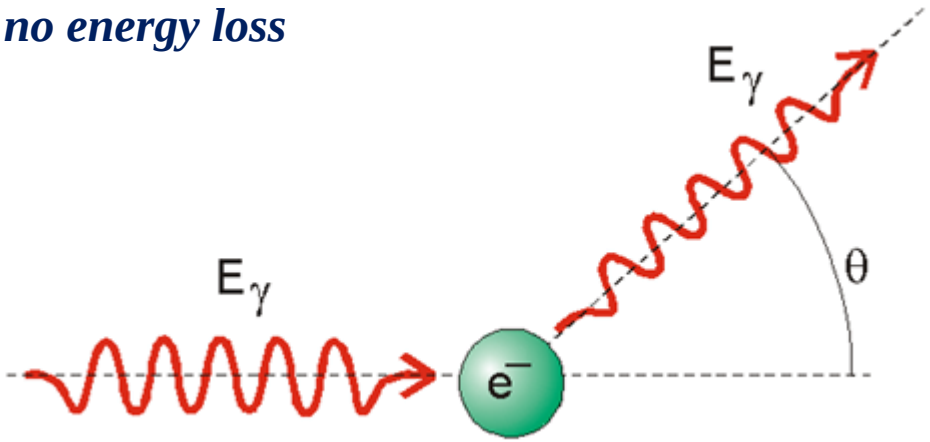
THOMSON SCATTERING

elastic scattering of el.-mag waves at a free charges = electron, …

independent of wave length λ

$$\sigma_{Th,\,e} = \frac{8\pi}{3} \cdot r_e^{\,2} \cong \frac{2}{3}\ barn$$

no energy loss



$$\sigma_{Th,\,atom} = Z \cdot \sigma_{Th}$$

deviates from experiment

$$r_e = \alpha \cdot \frac{e^2}{4\pi\epsilon_0 m_e c^2} = \alpha \cdot \frac{\hbar c}{m_e c^2} = 2.82 \cdot 10^{-15}\ m$$

application: plasma diagnosis, polarization of CMB, …

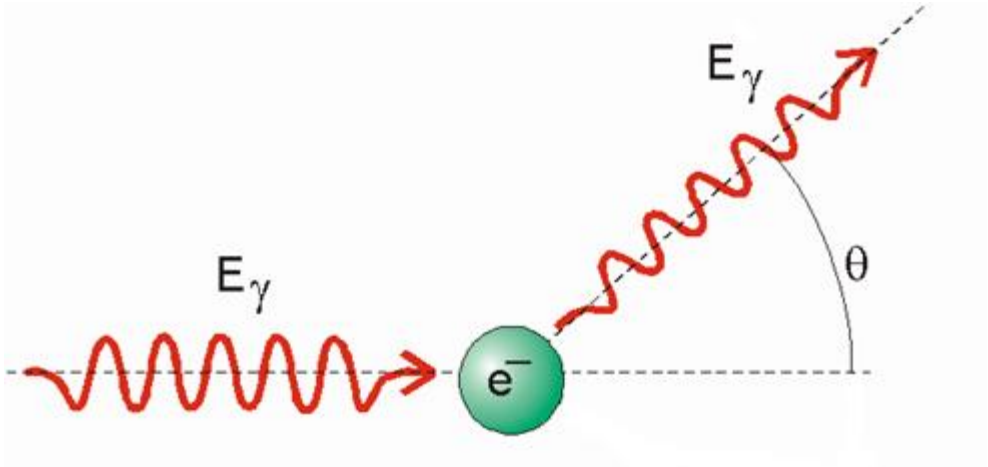
RAYLEIGH SCATTERING

elastic scattering of el.-mag waves at polarisable scattering centers = atoms, molecules

damped oscillation of „elastically“ bound electrons

eigen frequency ω_0

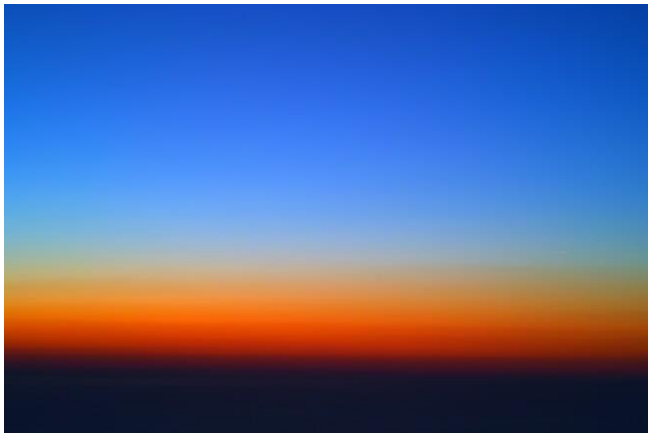
no energy loss



$$\sigma_R = \sigma_{Th} \cdot \frac{\omega^4}{(\omega^2 - {\omega_0}^2)^2} \cdot Z^2$$

ω_0 *eigen frequency*

$\omega \ll \omega_0$ *makes the sky blue / sunset red*



application: combustion diagnosis, holidays, …

PHOTO EFFECT ✓

requires particle nature of „light“ Einstein 1905

$$\sigma_{2K} = \sigma_{Th} \cdot 4\sqrt{2}\alpha^4 \cdot Z^{4-5} \cdot \varepsilon_\gamma^{-7/2}$$

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

1. photon disappears

   photo electron $E_e = E_{photon} - E_B$

2. refilling of hole in electron shell by

   a) emission of photon or

   b) Auger electron emission of loosely bound outer electron

   $E_{Auger} \cong E_B$

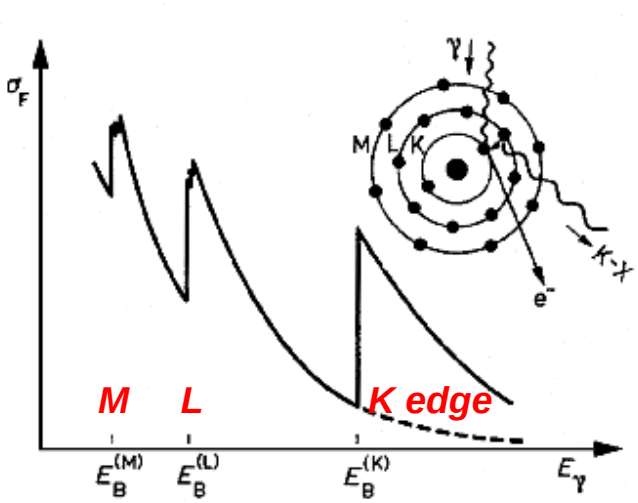
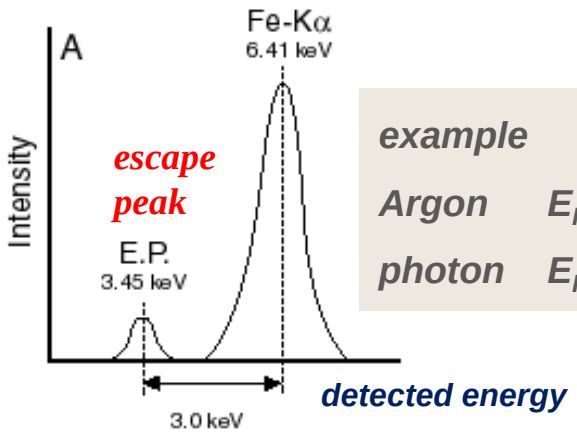


photo peak



detected energy E

photo peak $E = E_{photon} = E_e + E_B$

escape peak $E = E_{photon} - E_{K\alpha}$

example

Argon $E_{K\alpha} = 2.95$ *keV*

photon $E_{Photon} = 6.41$ *keV*

COMPTON EFFECT ✓

proof of particle nature of „light“ *Compton 1922*

billard with photons and „quasifree“ electrons

$$\sigma_C \approx \sigma_{Th} \cdot (1 - 2\varepsilon\gamma + \cdots) \cdot Z \qquad \varepsilon_\gamma \ll 1$$

$$\approx \sigma_{Th} \cdot \frac{3}{4} \cdot \left(\frac{1+2ln\varepsilon\gamma}{2\varepsilon\gamma} + \cdots\right) \cdot Z \qquad \varepsilon_\gamma \gg 1$$

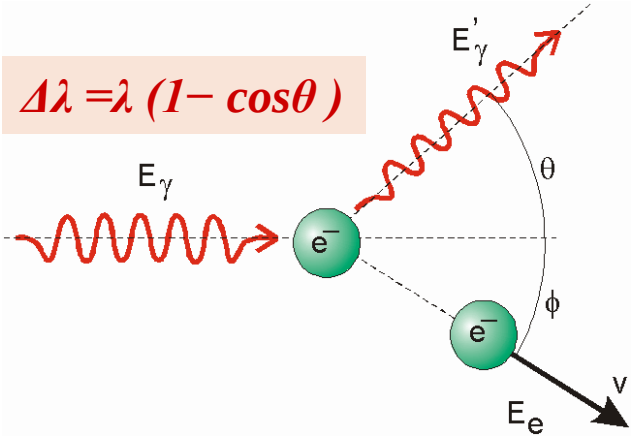
complicated QED calculation Klein&Nishina 1929

photon does not disappear

recoil electron $E_e = E_{photon} - E_{photon'}$

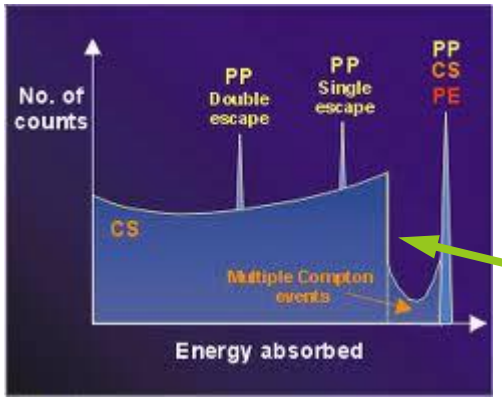
$\Rightarrow$ ***continuous spectrum***

$$\Delta\lambda = \lambda\,(1 - \cos\theta\,)$$



detected energy $E = E_e$

we neglegt E_B of the electron and E_{recoil} of the nucleus because usually E_B, $E_{recoil} << E_e$



Compton edge
= maximum energy transfer

PAIR PRODUCTION ✓

proof of mass-energy equivalence *Blackett 1948*

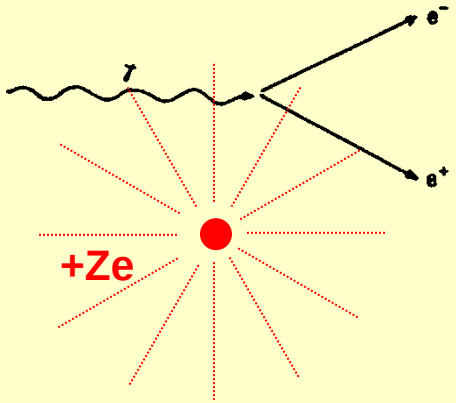
$$\sigma_{pair} \approx \sigma_{Th} \cdot Z^2 \cdot (ln 2\varepsilon\gamma + \cdots) \quad \varepsilon_\gamma \gg 1$$

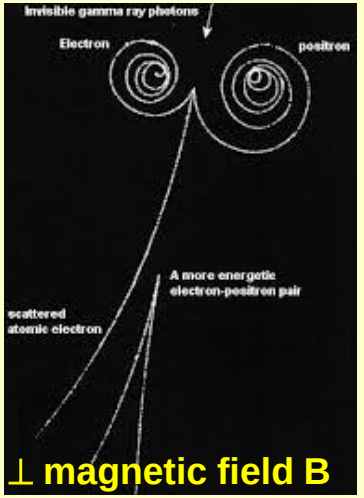
conversion of energy into matter

$E_{photon} = h\nu > 2\ m_{electron,muon,pion,\ \ldots}$

a recoil partner (e.g. a nucleus) is needed

to fulfil energy and momentum conservation





e^+e^- threshold: $m_{recoil} = \infty \quad h\nu = 2\ m_e c^2$

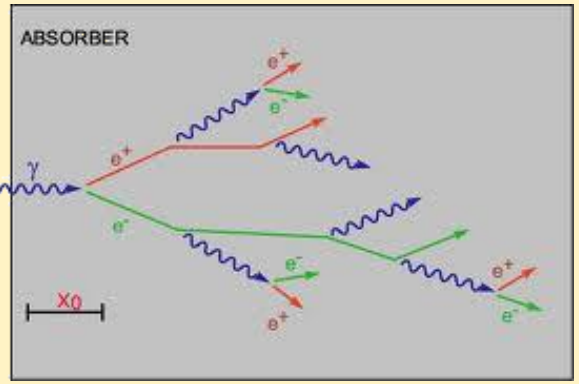
$= m_e \quad = 4\ m_e c^2$

el.-mag shower

$e^+\ e^-\ \gamma$ - cascade

pair production and bremsstrahlung alternate

shower may start with photon <u>or</u> electron

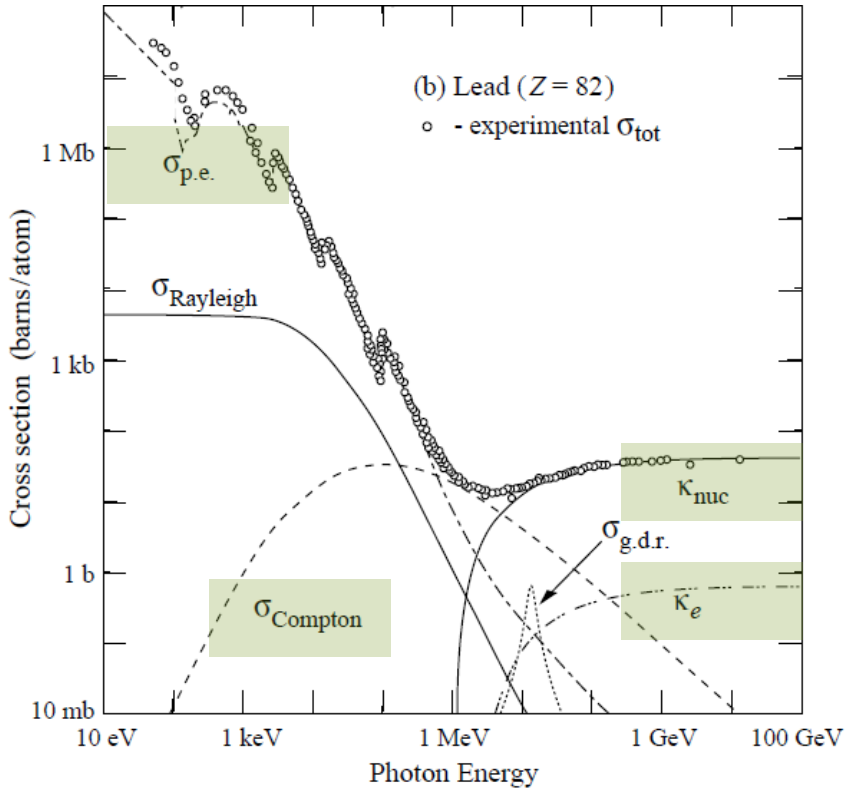


radiation length X_0

characteristic material dependent constant

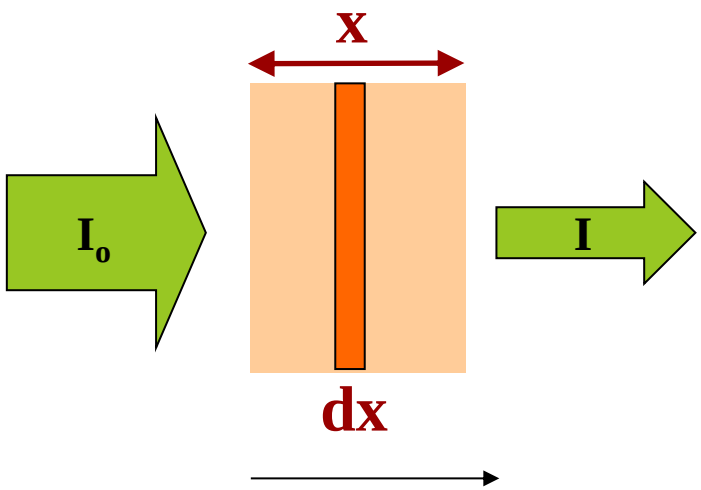
depth, where about 2/3 of the incident energy is converted

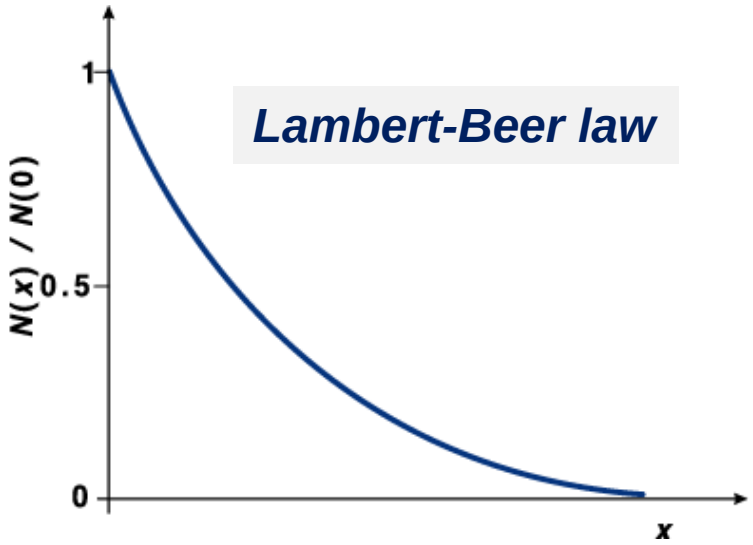
CROSS SECTIONS SUMMARY



$\sigma_{\text{p.e.}}$ = Atomic photoelectric effect (electron ejection, photon absorption)
σ_{Rayleigh} = Rayleigh (coherent) scattering–atom neither ionized nor excited
σ_{Compton} = Incoherent scattering (Compton scattering off an electron)
κ_{nuc} = Pair production, nuclear field
κ_e = Pair production, electron field
$\sigma_{\text{g.d.r.}}$ = Photonuclear interactions,

ATTENUATION





$$I(x) = I_0 e^{-\mu(h\nu)x}$$ *intensity after layer thickness x*

$$\frac{I_T(x)}{I_0} = e^{-\mu(h\nu)x}$$ *fraction of transmission*

$$\frac{I_A(x)}{I_0} = 1 - e^{-\mu(h\nu)x}$$ *fraction of absorption*

sum of linear attenuation coeff.

$$\mu(h\nu) = \sum_i \mu_i(h\nu)$$

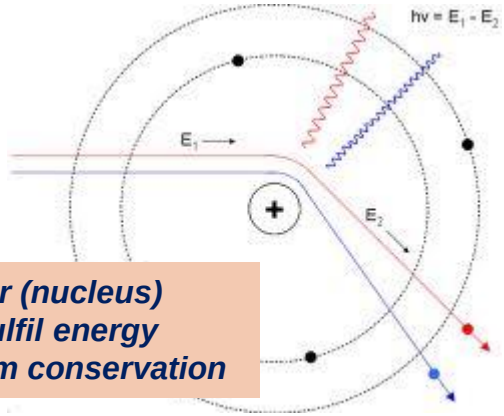
$$\mu_i = \rho \cdot \frac{N_A}{A} \cdot \sigma_i(h\nu)$$

BREMSSTRAHLUNG

accelerated charged particles radiate *Hertz 1886*

$$\sigma_b \approx \sigma_{Th} \cdot Z^2 \cdot [energy\ dependent]$$

electromagnetic waves

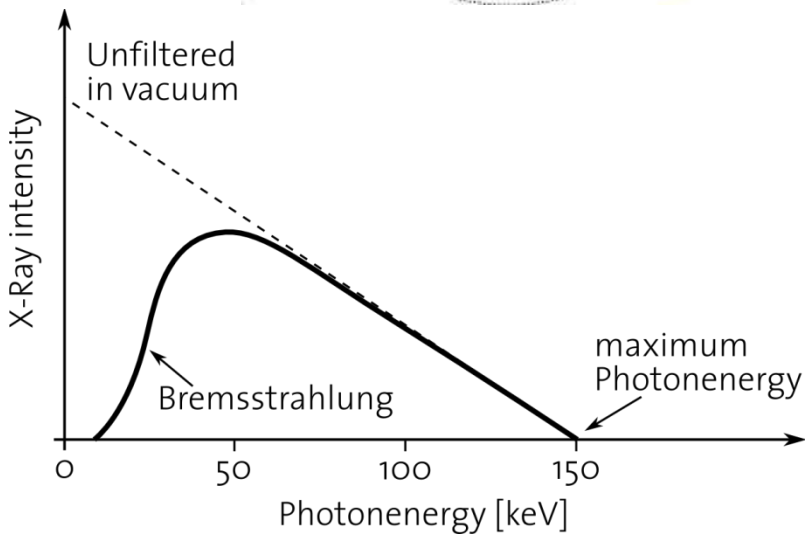


bending force by Coulomb potential

force ⇔ acceleration

a recoil partner (nucleus) is needed to fulfil energy and momentum conservation

$$F_{Coulomb} = \frac{1}{4\pi\varepsilon_0} \cdot \frac{Q_{particle} \cdot Q_{nucleus}}{r^2} = m \cdot \ddot{r}$$



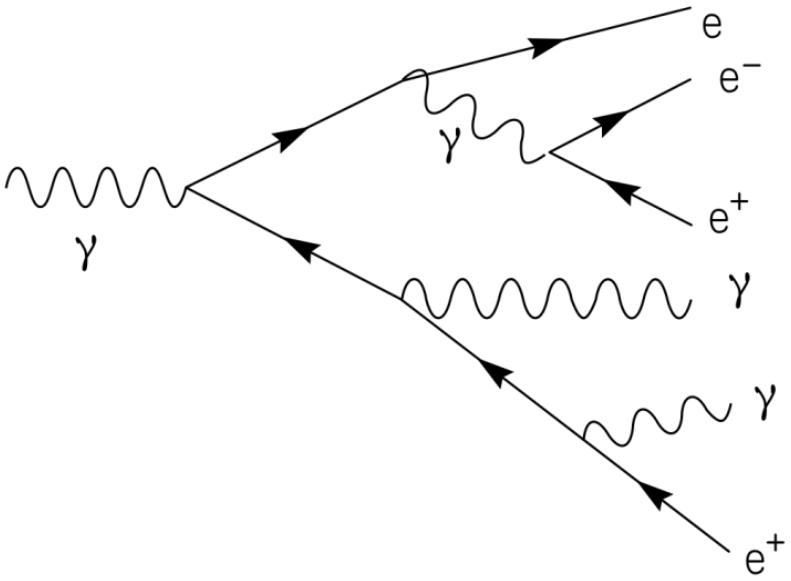
any distance r

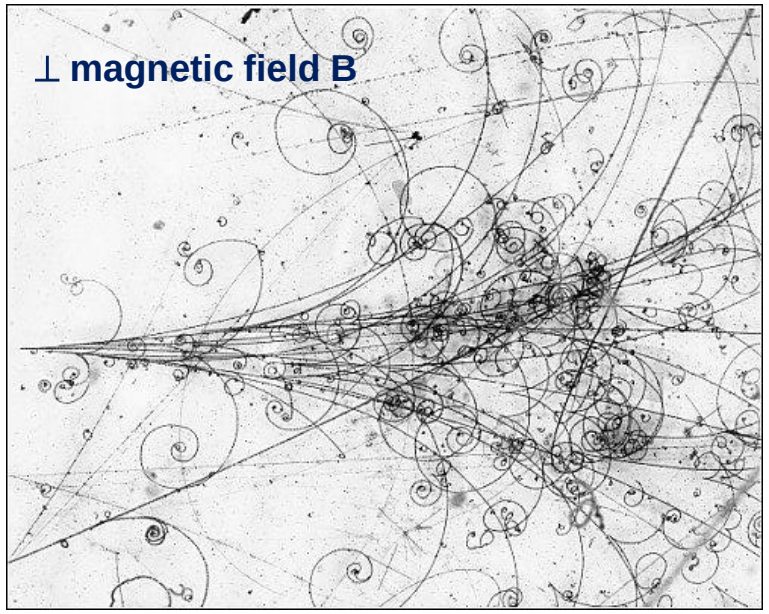
⇒ continuous spectrum

EL.-MAG. SHOWER

alternating pair production & bremsstrahlung

initial particle of minor importance for large energies





characteristic quantity of absorber

radiation length X_0

x

$$E_\gamma = E_{initial} \cdot e^{-(x/X_0)}$$