INTERACTION of

PARTICLES and RADIATION with MATTER

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- **INTRODUCTION**
- **PLAYGROUND**
- **HOW TO DETECT ?**
- **RADIATION**
- **MASSIVE PARTICLES**

INTRODUCTION

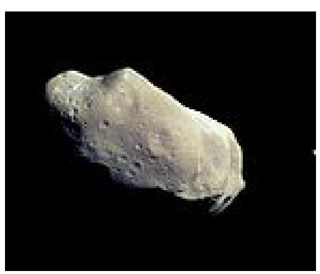
PLAYERS in the SUB-ATOMIC WORLD

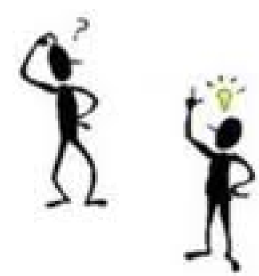
PLAYERS I: PARTICLES

particle | detector | registration

Light

Heavy



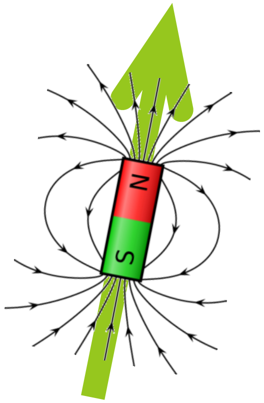


PARTICLES

What characterizes a particle?

mass m *includes* $m = 0$

charge Q



Spin *intrinsic angular momentum* S ⇔ ***magnetic moment*** μ

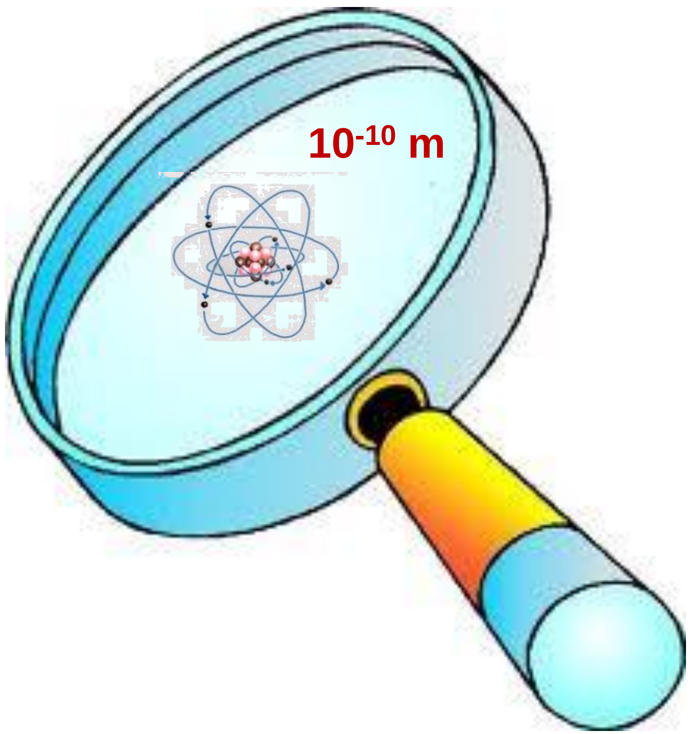
life time τ_0

size *for non elementary particles* $\sqrt{\langle r^2 \rangle}$ *root-mean square radius*

quantum mechanics $\lambda = \frac{h}{p}$ ***matter waves (de Broglie 1922)***

PARTICLES in 1932

atoms



	atomic shells	nucleus	
	electron **e**	**proton** **p**	**neutron** **n**
Q	**– 1**	**+ 1**	**0**
M	**M_p / 1836**	**M_p**	**≈ M_p**
S	½	½	½
size	$< 10^{-18}$ m	$0.8 \cdot 10^{-15}$ m	
life time τ_0	$> 10^{26}$ y	$> 10^{29}$ y	886 s
decay	-	-	$n \rightarrow p\, e^- \bar{\nu}$

PARTICLES …

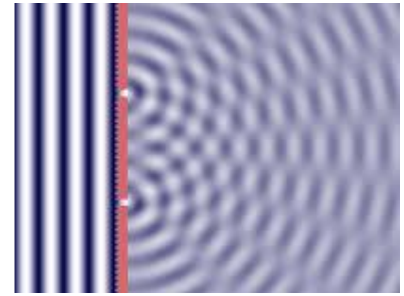
new particles – unstable being free

		pions		kaons	many more
		π		K	…
Q		$0, \pm 1$		$2 \times 0, \pm 1$	
M		$\approx M_p / 7$		$\approx M_p / 2$	
S		0		0	$0, {}^{1}/_{2}, 1, {}^{3}/_{2}, 2, \dots$
size		$0.6 \cdot 10^{-15}$ m		$0.6 \cdot 10^{-15}$ m	
life time τ_0	$\pi^{\pm}$	$26 \cdot 10^{-9}$ s	$K^{\pm}$	$12 \cdot 10^{-9}$ s	
	π^0	$8 \cdot 10^{-17}$ s	$K^0_{S,L}$	$9 \cdot 10^{-10} / 5 \cdot 10^{-8}$ s	
decay		$\pi^{\pm} \rightarrow \mu^{\pm} \nu$		$K^{\pm} \rightarrow \mu^{\pm} \nu, \dots$	
		$\pi^0 \rightarrow \gamma \gamma$		$K^0 \rightarrow \pi^+ \pi^-, \pi^0 \pi^0, \dots$	

PLAYERS II: WAVES

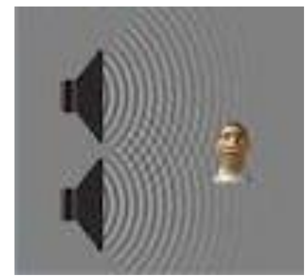
fluid



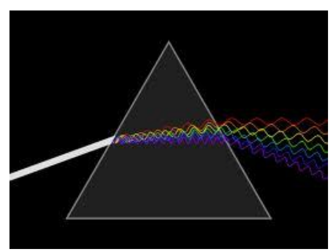
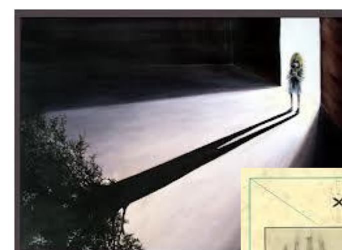
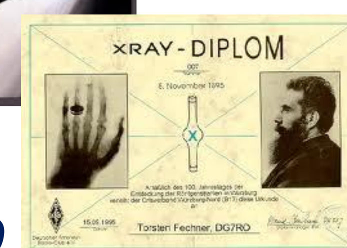


gas



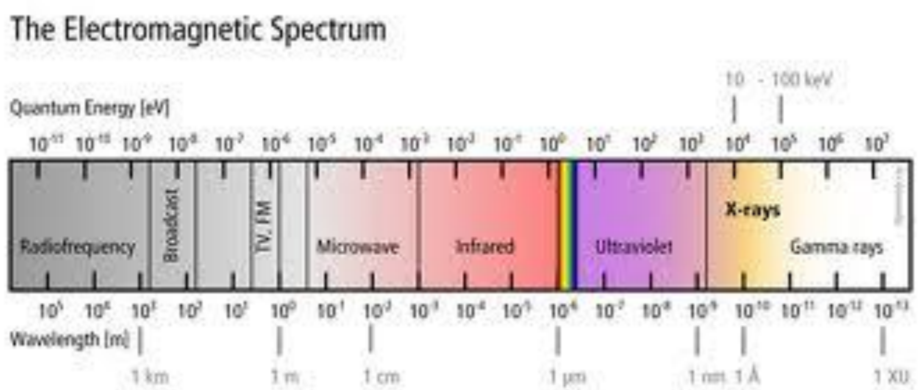


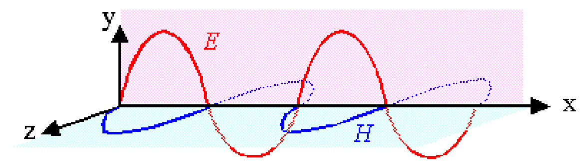
„light“

fundamental constant: c = speed of light in vacuum (≅30 cm / ns)

ELECTROMAGNETIC RADIATION





wave length λ

frequency ν

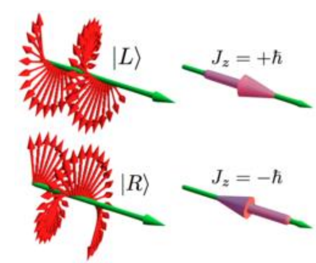
wave propagation velocity in vacuum $c = \lambda\, \nu$

" " " in medium $c' = \lambda' \nu < c$

index of refraction $n = c / c'$

quantum mechanics: waves can be particles

Photon **S = 1** $m = \pm 1$, **no** $m = 0$



left/right circular polarization

having energy $E = h\nu = \dfrac{hc}{\lambda}$

(Einstein 1905)

COMPARISON

	massive particles		el.-mag. radiation	
total energy	$\mathbf{E_{total}} = \sqrt{\mathbf{p^2c^2 + m_0^2c^4}}$ $= \gamma\, \mathbf{m_0c^2}$ $\mathbf{T_{kin}} = \mathbf{E_{total}} - \mathbf{m_0c^2}$		$\mathbf{E_{total}} = \mathbf{pc}$ $= \mathbf{h\nu}$ $= \hbar\,\boldsymbol{\omega}$	***h* Planck constant** ***h* = minimal action** $\left(\hbar = \frac{h}{2\pi}\right)$
rest mass	$m_0 \neq 0$	*range in matter*	$= 0$	*attenuation in matter*
charge	$Q \neq 0$	*deflection in el.-mag fields*	$= 0$	*no deflection*
life time	$\tau = \gamma\tau_0$	*decay length* $\boldsymbol{l = v\,\tau}$	$= \infty$	

relativistic factor $\quad \gamma = \dfrac{1}{\sqrt{1-\beta^2}}, \quad \beta = \dfrac{v}{c} \quad \lim \gamma \xrightarrow[v \to c]{} \infty$

PLAYGROUND

by means of „normal“ matter

ATOMS and NUCLEI I

Each substance is composed of chemical <u>elements</u> ≡ basic set of atoms **(Dalton, …)**

1 Mol Na + 1 Mol Cl → 1 Mol NaCl

1 Mol contains always the same number of particles $N_A = 6{\cdot}10^{23}$

The ratios of molar masses of the elements are almost ratios of integer numbers.

Atomic mass unit (a.m.u.)

$$1\,\mathbf{a.m.u.} = \frac{\mathbf{m(^{12}C\,atom)}}{12} = \frac{12\,\mathbf{g}}{12\cdot \mathbf{N_A}} = 1.66\,10^{-27}\,\mathbf{kg}$$

Periodic system of elements

Mendelejev: Ordering scheme according to chemical properties

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt	...	...	...						

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

ATOMS and NUCLEI II

Discovery of the electron (J.J. Thomson 1897)

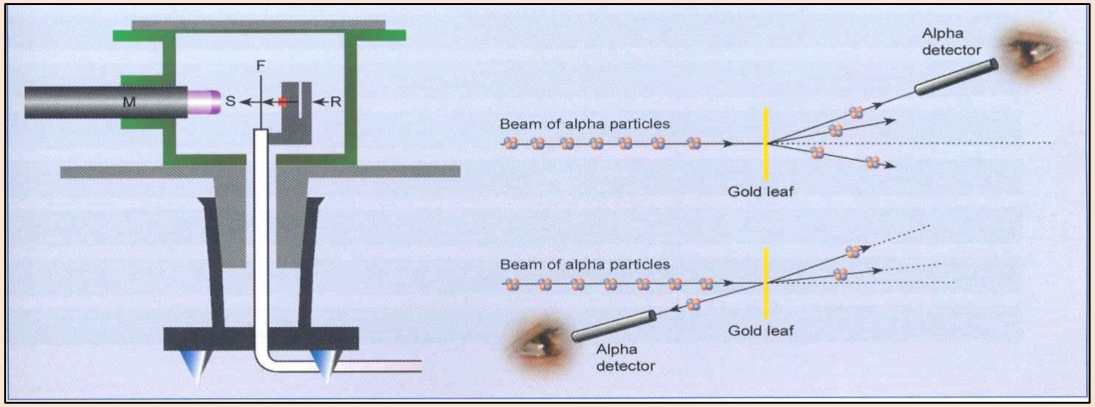
Interpretation of the rays accompanying gas discharges:
Kathode rays: Electrons (negatively charged and light)
Channel rays: Ions (positively charged and heavy)

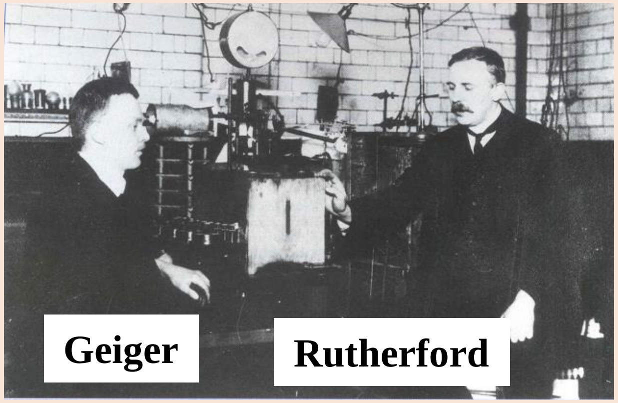
$$\mathbf{m_e = \frac{1}{1836} \cdot m_u, \; q_e = -e}$$

Discovery of the atomic nucleus (Geiger & Rutherford 1911)

Almost the full mass of an atom of diameter ~ 10^{-10} m is concentrated in a tiny volume of radius ~ 10^{-15} m

Proof: Collision kinematics – backscattering only from heavy collsion partners





$\Rightarrow$ *total atom is electrical neutral: Atomic nucleus - electric charge* $+Z\,q_e$ *Z positive integer*
Atomic shell - electric charge $-Z\,q_e$

ATOMS and NUCLEI III

Bohr-Sommerfeld model of atoms

main quantum number $n = 1, 2, \ldots$

"main shell"

angular momentum $\ell = 0, \ldots, n-1$

„sub-shell"

magnetic quantum number $m = -\ell, -\ell+1, \ldots, \ell-1, \ell$

$(2\ell+1)$ possible orientations of angular momentum vector in external field

intrinsic electron spin $S = ½$

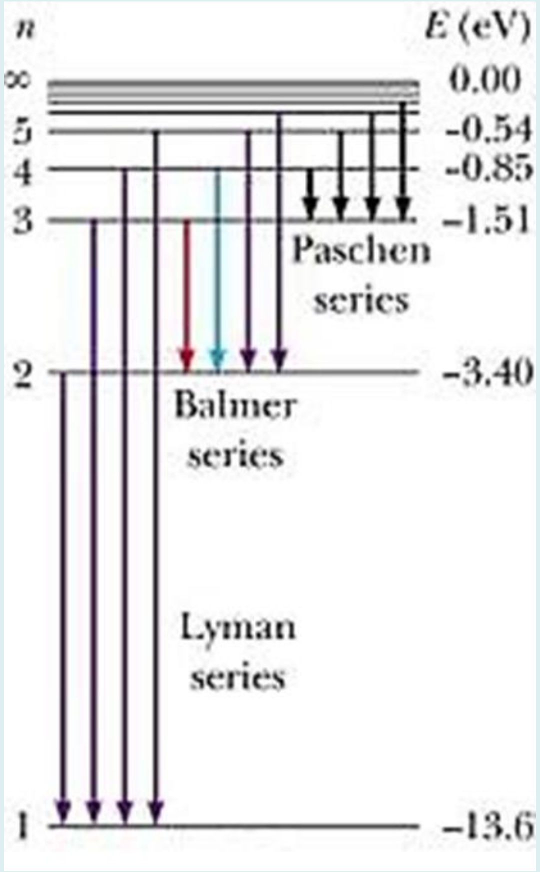
intrinsic angular momentum

2 possible orientations of spin vector in external field $S = \pm ½$

total spin: $\vec{j} = \vec{\ell} + \vec{S}$ $|\vec{j}| = \frac{1}{2}, 1, \frac{3}{2}, \ldots$

ℓ and S are measured in units $\hbar$

main shells for Z = 1 (H)



ATOMS and NUCLEI IV

S = ½ ***particles are called fermions***

Pauli principle:

Only one fermion is allowed in a particular quantum state: For atoms = (n, ℓ, m, S)

⇒ maximum no. of electrons per sub-shell: $2\cdot(2\ell + 1)$

Periodic system of elements

$A(Z,N) + Ze^-$

Mendelejev: Ordering scheme according to chemical properties

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt	...	...	...						

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

outmost incomplete shell determines chemistry

FORCES

strength

Standard Model

- **nuclear force** — ***keeps protons and neutrons together***
- **electromagnetic force** — ***keeps electrons around the nuclei***
- **weak force** — ***makes the (free) neutron to decay***
- **gravitation** — ***keeps us on the ground***

HOW TO DETECT ?

„via“ electric force !

SIGNAL CREATION

- **access via electric charges**
- **produced in elementary processes with atoms and nuclei**

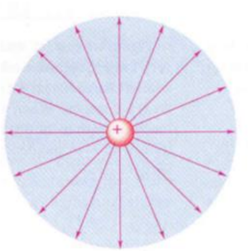
EL.-MAG. INTERACTION I - ELECTRIC FORCE

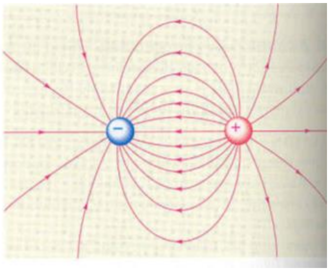
the force is mediated in the

classical picture

by field around a source

$$F_{Coulomb} = \frac{1}{4\pi\varepsilon_0} \cdot \frac{Q_1 Q_2}{r^2}$$

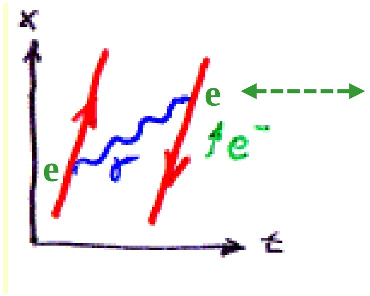




quantum world

field quanta = „virtual“ particles

„light“ particles = photons γ



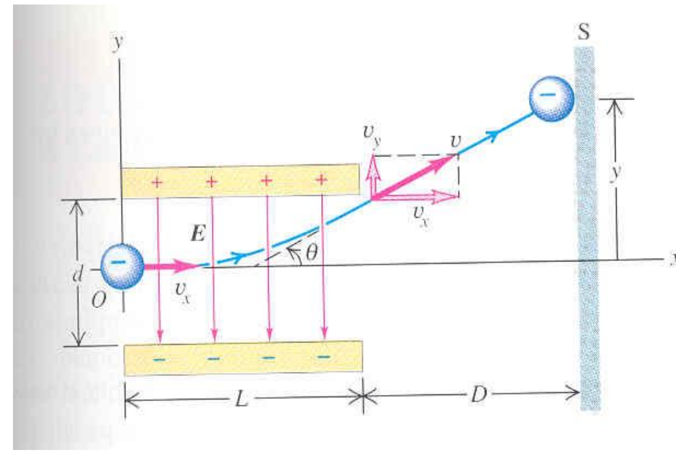
coupling $\alpha = \frac{e^2}{4\pi\epsilon_0 \hbar c} = \frac{1}{137}$

electromagnetic radiation = E and B fields interact with electric charges

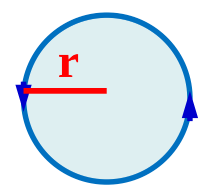
EL.-MAG. INTERACTION II - CHARGES in EL.-MAG. FIELDS

- **electric field** $\vec{F} = m\ddot{\vec{x}} = Q \cdot \vec{E}$

$\Rightarrow \quad \dfrac{Q}{M}$



- **magnetic field** $\vec{F} = m\ddot{\vec{x}} = Q \cdot \left(\vec{v} \times \vec{B}\right)$



B = const.

$\Rightarrow$ *circular motion*

B ⊥ plane of projection

$\omega = \dfrac{Q}{M} B \qquad \omega = \dfrac{2\pi}{T}$

$\Rightarrow \quad p$

$$mv^2 / r = Q \cdot v \cdot B$$
$$p = Q \cdot B \cdot r$$

INTERACTION OF

ELECTRO – MAGNETIC RADIATION

SCATTERING

EXCITATION - SCINTILLATORS produce “LIGHT”

PHOTO EFFECT

COMPTON EFFECT

PAIR PRODUCTION

BREMSSTRAHLUNG & EL.-MAG. SHOWER

ATTENUATION

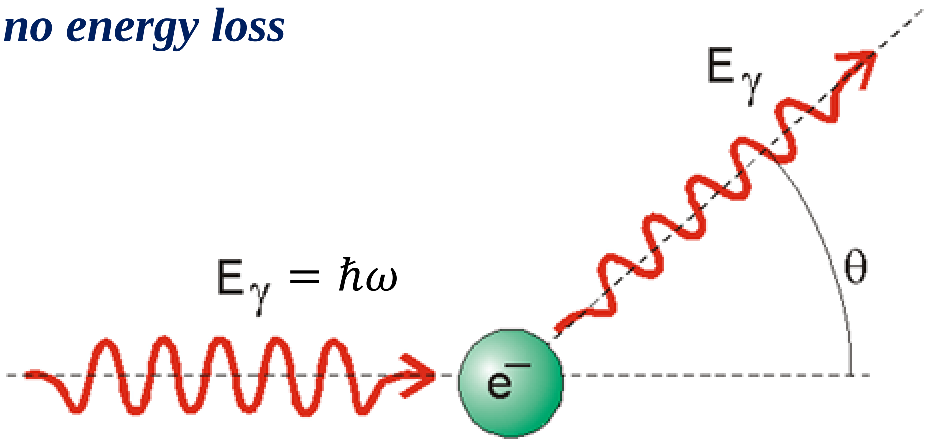
THOMSON SCATTERING

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

independent of wave length λ

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

no energy loss



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

deviates from experiment

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

application: plasma diagnosis, polarization of CMB, …

RAYLEIGH SCATTERING

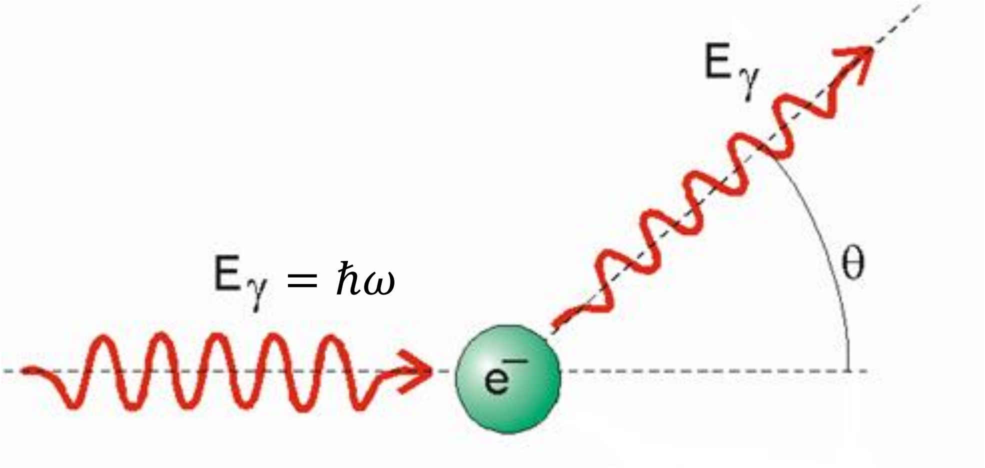
elastic scattering of el.-mag. waves at polarisable scattering centers = atoms, molecules

damped oscillation of „elastically“ bound electrons

eigen frequency ω_0 of bound system

no energy loss

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



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

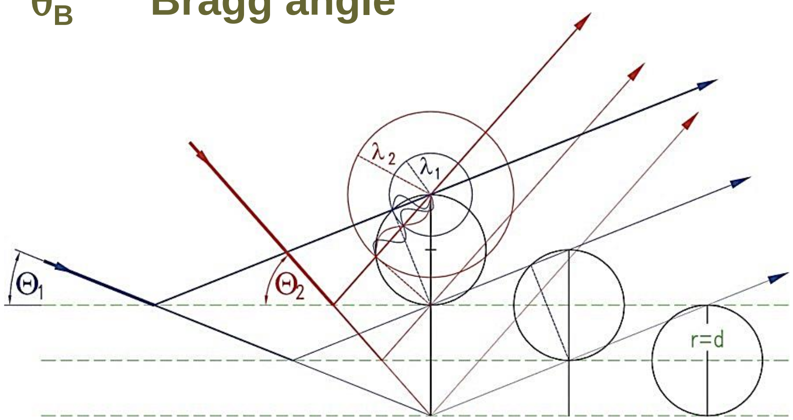
application: combustion diagnosis, holidays, …

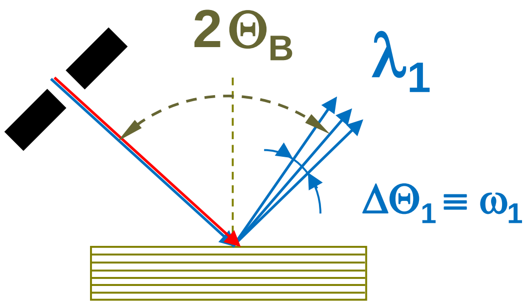
COHERENT SCATTERING - BRAGG'S LAW

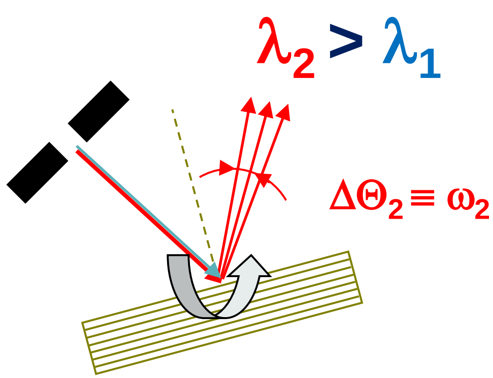
$$n\lambda = 2d \cdot \sin\theta_B$$

ω angular spread of „reflection“

n	order of diffraction
λ	wave length
d	spacing of diffracting planes
θ_B	Bragg angle





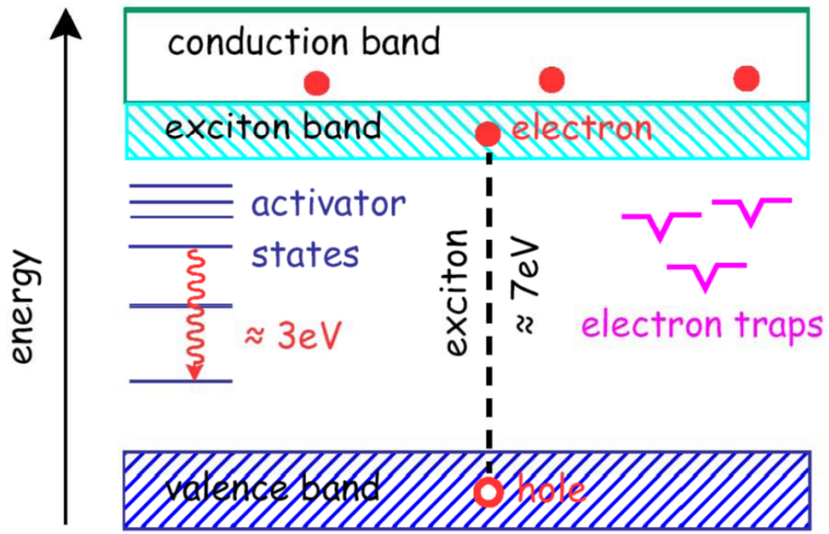


e.g. wave length of $\lambda = 60\ pm$

electromagnetic wave — *20 keV X-rays (dentist)*

matter wave — *T = 0.2 eV, v = 60 cm/s (epithermal neutrons)*

EXCITATION - SCINTILLATORS produce "LIGHT"



ionisation caused by

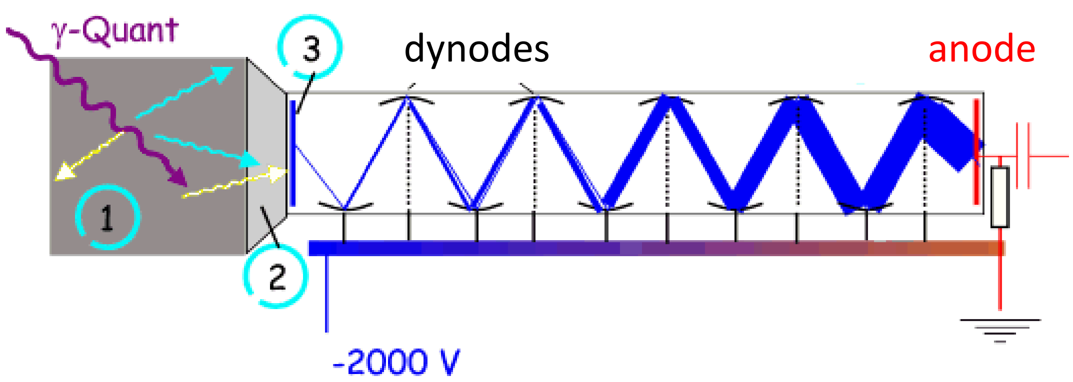
⇒ **charged particles or light**

excitation and delayed light emission

usually in the UV range

scintillators ①

inorganic	**NaI(Tl), CsI, BaF_2, …**
organic	***doped „plastics"***



② light coupling

UV light is converted to charge

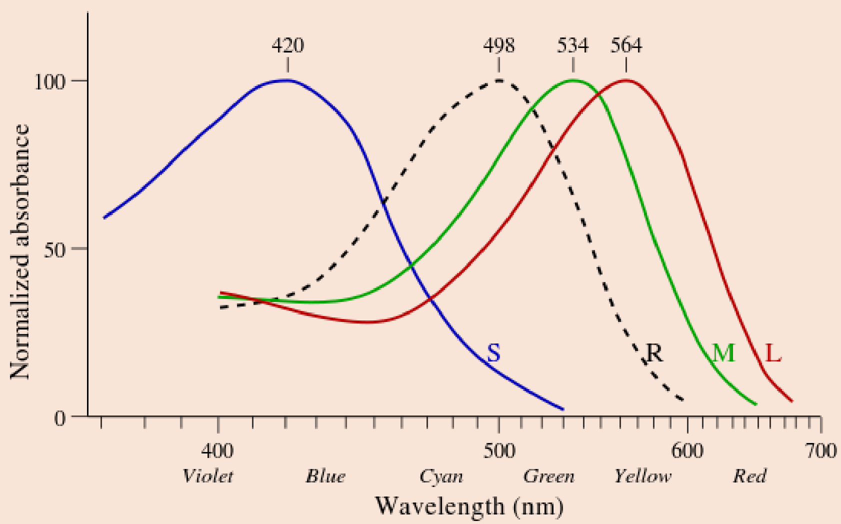
at a photo cathode ③ and

multiplied by a multi stage (dynodes)

photo „multiplier"

EXCITATION - RESPONSE of EYE CELLS

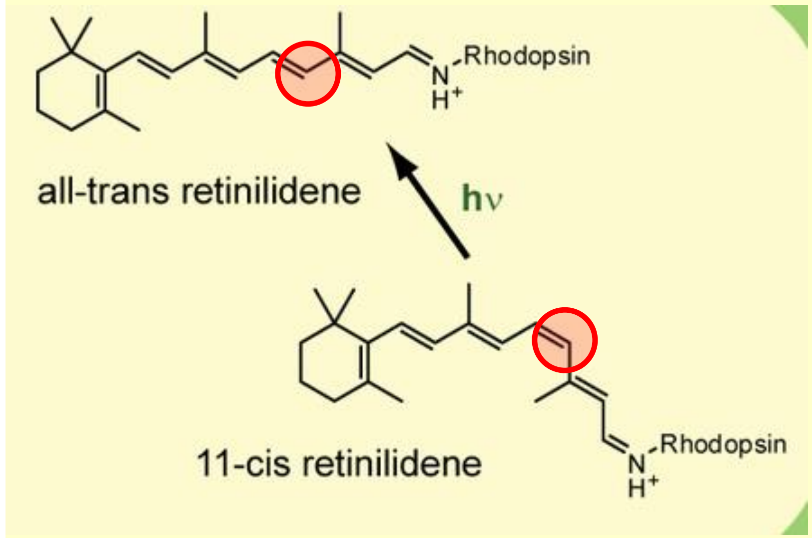
sensitivity *1 photon*



cone cells

rod cells

sensitivity *100 photons*



cis – trans transition

of various opsin (protein) molecules

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 $E_e = E_{photon} - E_B$

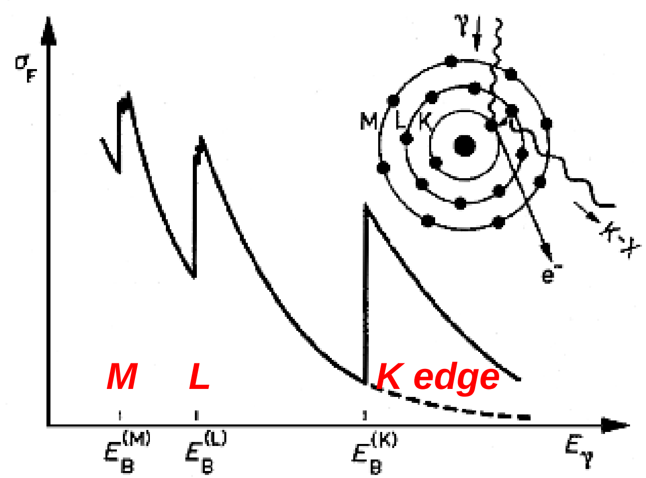
2. refilling of hole in electron shell by

   a) emission of photon or

   b) Auger electron emission of

   loosely bound outer electron

   $E_{Auger} \cong E_B$

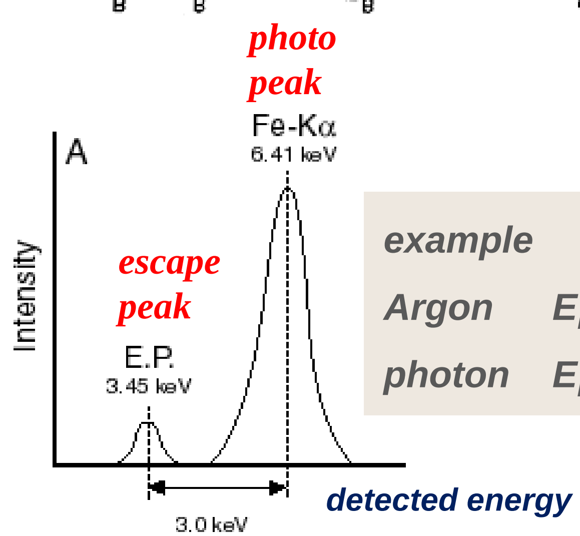


detected energy E

photo peak $E = E_{photon}$

$= E_e + E_B$

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



example

Argon	$E_{K\alpha}$	*= 2.96 keV*
photon	E_{Photon}	*= 6.41 keV*

COMPTON EFFECT

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

billard with photons and „quasifree“ electrons

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

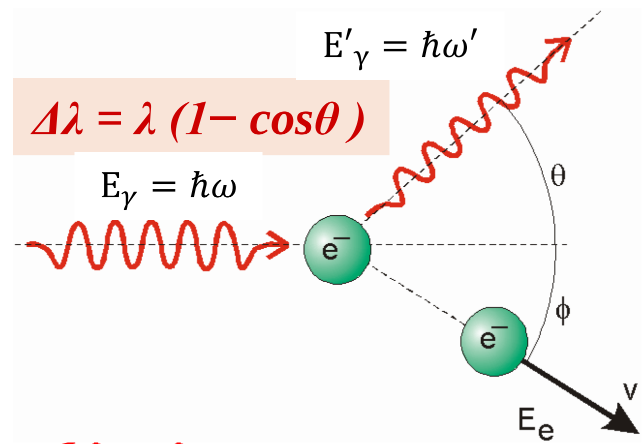
$$\approx \sigma_{Th} \cdot \frac{3}{4} \cdot \left(\frac{1+2\ln\varepsilon\gamma}{2\varepsilon\gamma} + \cdots\right) \cdot Z \qquad \varepsilon_\gamma \gg 1$$

complicated QED calculation Klein&Nishina 1929

photon does not disappear

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

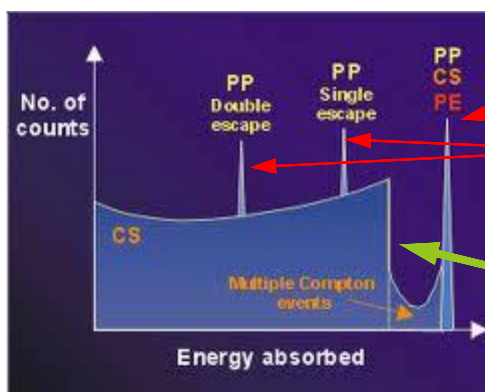
$\Rightarrow$ *continuous spectrum*



detected energy E

= absorbed energy E_e

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



escape peaks

Compton edge
= maximum energy transfer

PAIR PRODUCTION

proof of mass-energy equivalence ***Blackett 1948***

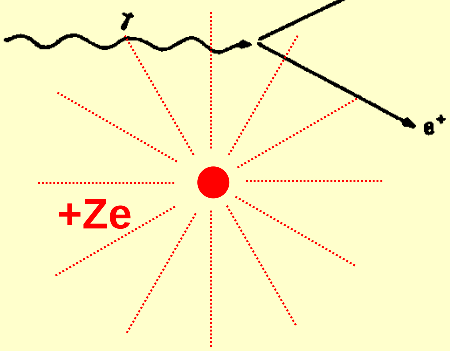
$$\sigma_{pair} \approx \sigma_{Th} \cdot Z^2 \cdot (ln2\varepsilon\gamma + \cdots) \quad \varepsilon_\gamma \gg 1$$

conversion of energy into matter

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

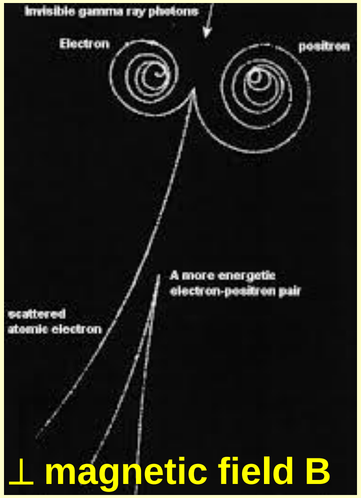
a recoil partner (e.g. a nucleus) is needed

to fulfil energy and momentum conservation



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

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

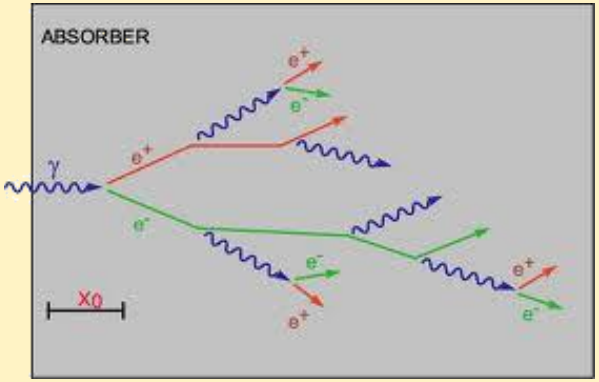


el.-mag. shower

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

pair production and bremsstrahlung alternate

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



radiation length X_0

characteristic material dependent constant

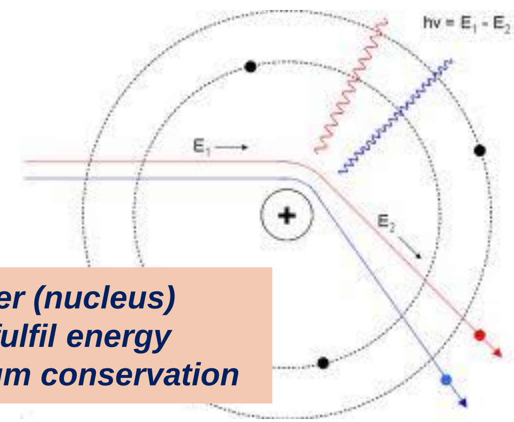
depth, where about 2/3 (1/e) of the incident energy is converted

BREMSSTRAHLUNG

accelerated charged particles radiate *Hertz 1886*

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

electromagnetic waves

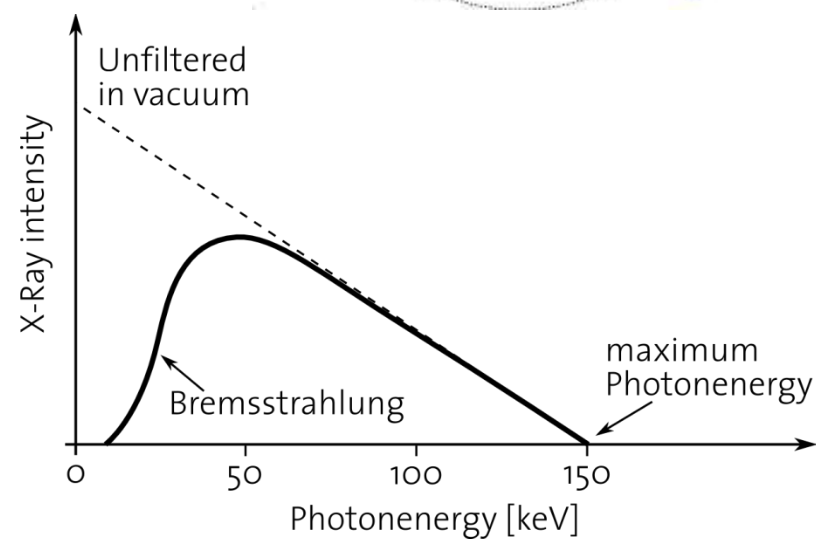


bending force by Coulomb potential

force ⇔ acceleration

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

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



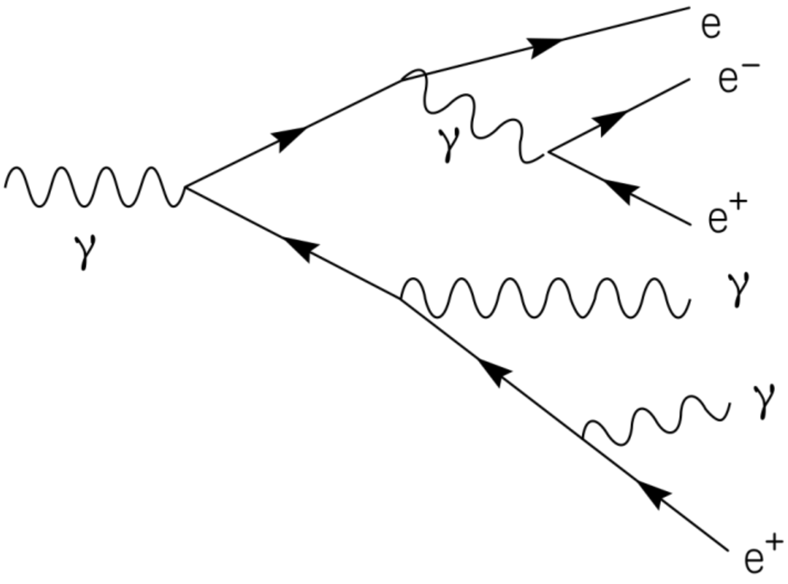
any distance r

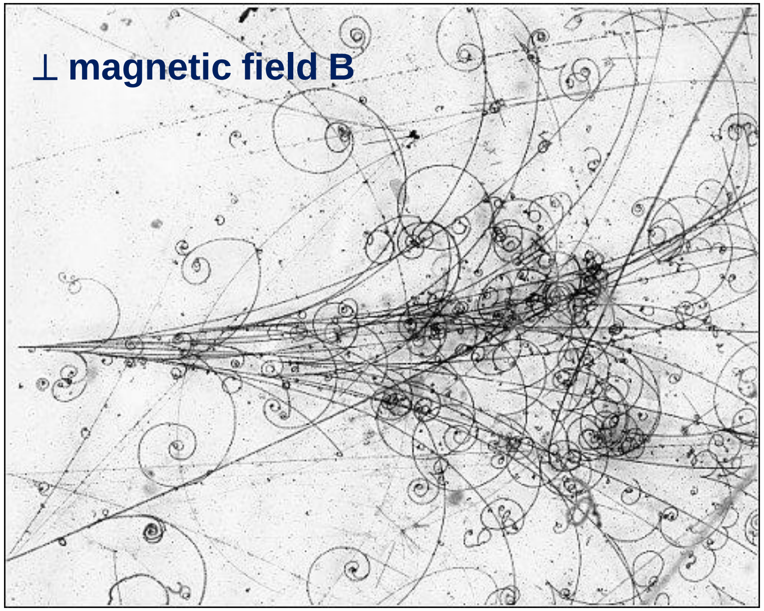
⇒ continuous spectrum

EL.-MAG. SHOWER

alternating pair production & bremsstrahlung

initial particle of minor importance for large energies





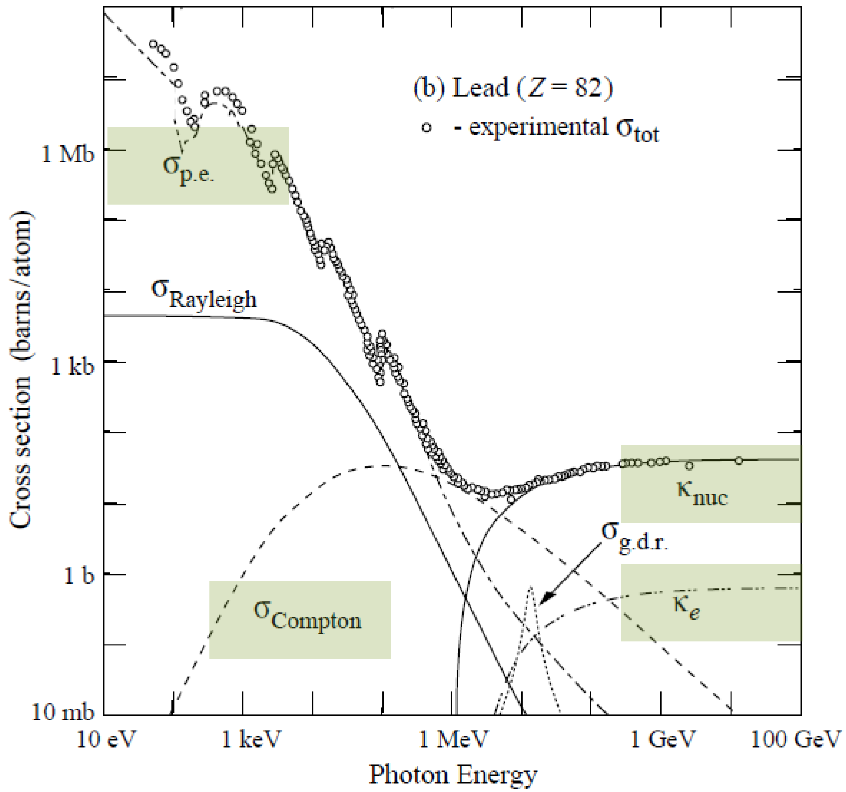
radiation length X_0

x

characteristic quantity of absorber

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

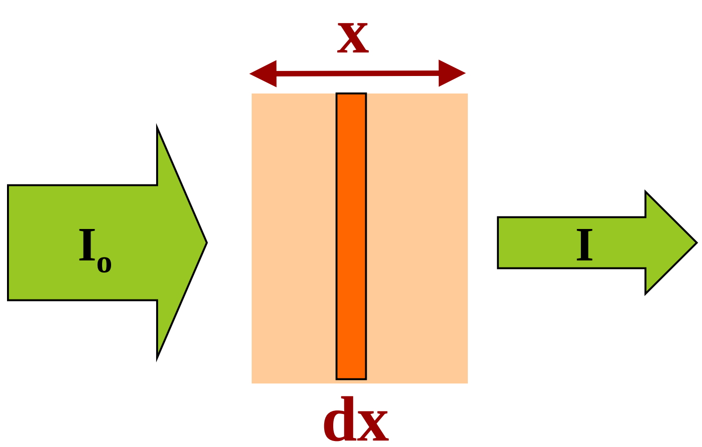
CROSS SECTIONS SUMMARY

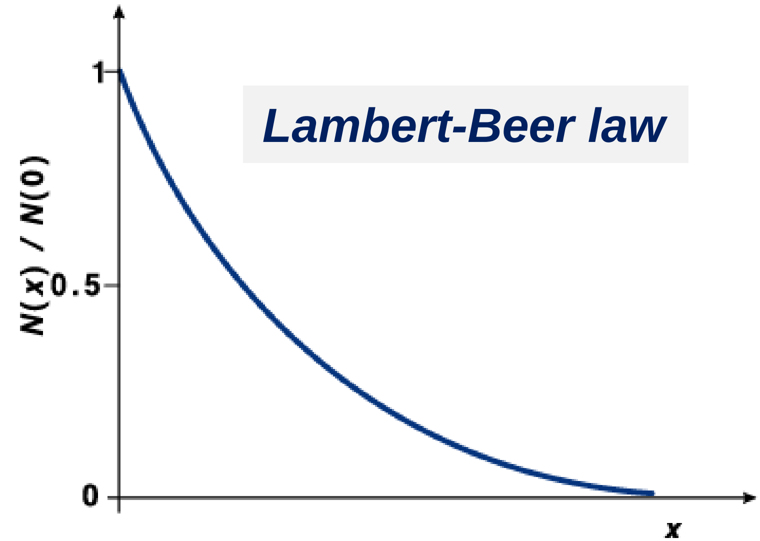


from
C. Patrignani *et al.*
(Particle Data Group),
Chin. Phys. C, **40**, 100001 (2016).

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

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.

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

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

INTERACTION OF

MASSIVE PARTICLES

CHARGED PARTICLES : ENERGY LOSS BY IONIZATION

HEAVY CHARGED PARTICLES

LIGHT CHARGED PARTICLES

CHARGED PARTICLES : ENERGY LOSS BY RADIATION

NEUTRONS

CHARGED PARTICLES

interaction happens by collisions of particles type 1 and 2

		before	**after collision**
1.	$M_{particle\ 1} >> M_{particle\ 2}$		
2.	$M_{particle\ 1} = M_{particle\ 2}$	 	

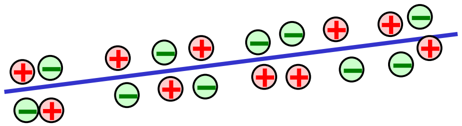
CHARGED PARTICLES - ENERGY LOSS by IONIZATION

collisions create electron- ion pairs

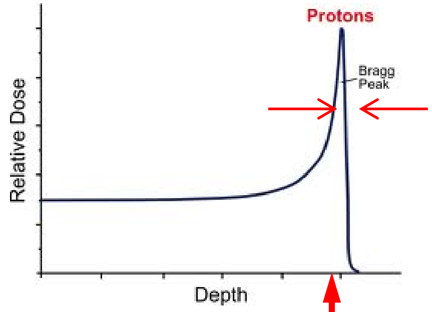
Bragg peak

1. ***heavy*** $M_{particle} >> M_{electron}$

e.g. protons, deuterons, …



strongly ionising



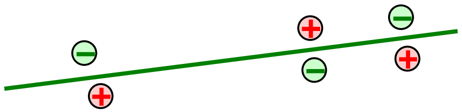
$$\frac{\Delta R}{R} = 1 - 3\%$$

for all elements

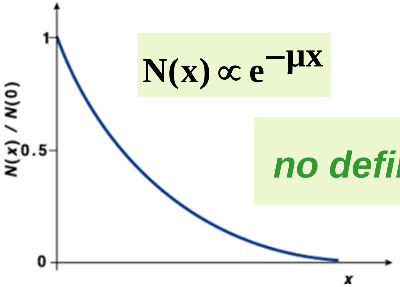
well defined range R!

2. ***light*** $M_{particle} = M_{electron}$

electrons or positrons



weakly ionising



$$N(x) \propto e^{-\mu x}$$

no defined range R!

exponential attenuation with depth x

μ: material dependent attenuation coefficient

INTERACTION OF

HEAVY CHARGED PARTICLES

WITH MATTER

HEAVY CHARGED PARTICLES - STOPPING POWER I

heavy particles μ, π, **K, p, d, …**

stopping power

$$S = \left(-\frac{dE}{dx}\right) \cdot \frac{1}{\rho}$$

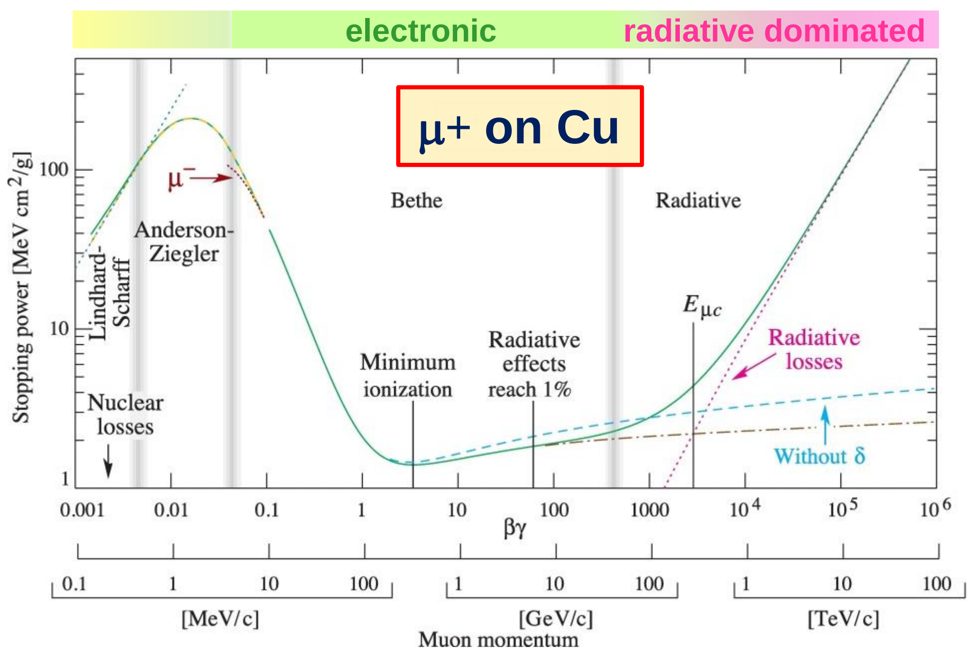
[MeV· cm²/g]

$\beta < \alpha \approx \beta_{\text{valence electron}}$

$\alpha < \beta < 0.1$ β_{electron} **neglected**

$\beta = 0.7$

$\beta = 1 - 10^{-7}$



from
C. Patrignani *et al.*
(Particle Data Group),
Chin. Phys. C, **40**, 100001 (2016).

HEAVY CHARGED PARTICLES - STOPPING POWER II

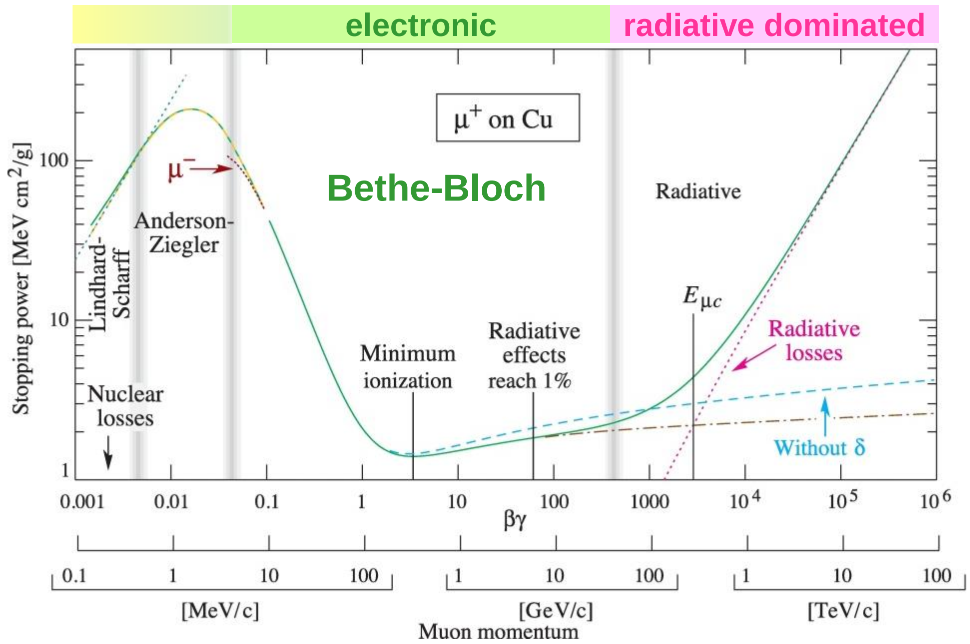
Bethe-Bloch range

$\alpha < \beta < 0.1$: $\beta_{electron}$ neglected

stopping power

$$S = \left(-\frac{dE}{dx}\right) \cdot \frac{1}{\rho}$$

$[MeV \cdot cm^2/g]$



C_0 shell corrections for low energies

$$S = 4\pi N_A r_e^2 m_e c^2 \frac{Z_{target}}{A} \cdot \frac{z^2_{projectile}}{\beta^2} \cdot \left[\frac{1}{2} ln\left(\frac{2m_e c^2 \beta^2 \gamma^2 T_e^{max}}{I^2}\right) - \beta^2 - \frac{C_0(\beta^2)}{Z_{target}} - \frac{\delta(\beta\gamma)}{2}\right]$$

HEAVY CHARGED PARTICLES - STOPPING POWER III

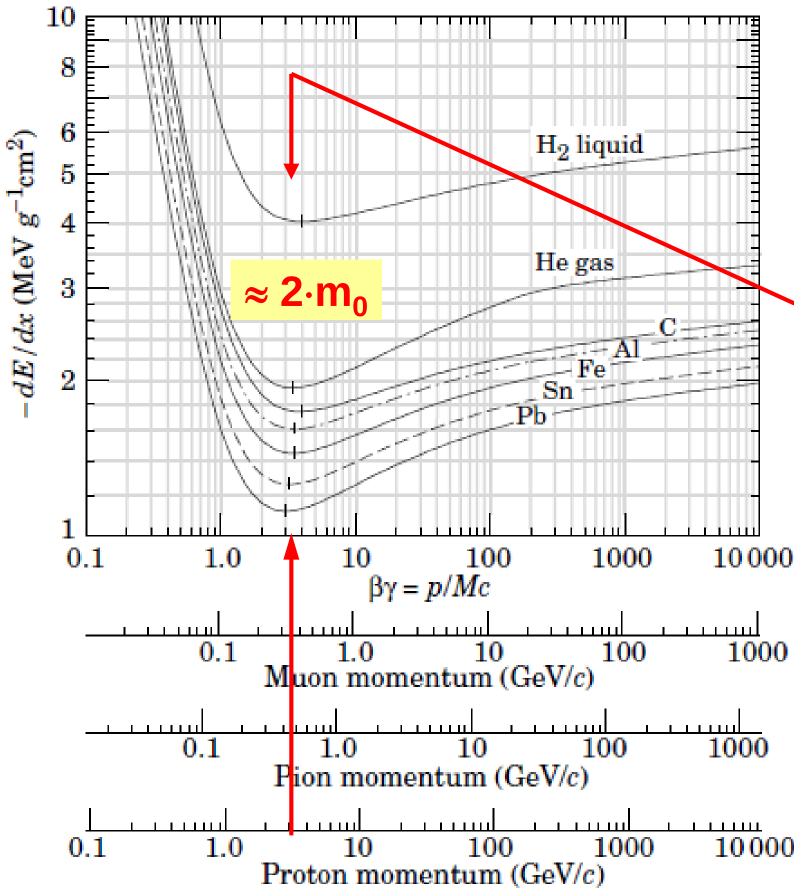


Figure 30.2: Mean energy loss rate in liquid (bubble chamber) hydrogen, gaseous helium, carbon, aluminum, iron, tin, and lead. Radiative effects, relevant for muons and pions, are not included. These become significant for muons in iron for $\beta\gamma \gtrsim 1000$, and at lower momenta for muons in higher-Z absorbers. See Fig. 30.23.

Bethe-Bloch range

$$\left(\frac{\Delta E}{\Delta x}\right)_{collision} \propto \frac{1}{v^2} \quad \ldots$$

MIPs = *minimum ionising particles*

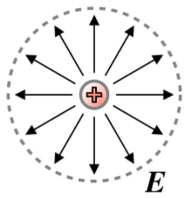
$$\left(-\frac{dE}{dx}\right)_{min} = 4\ MeV g^{-1} cm^2 \qquad for\ \ A = 1$$

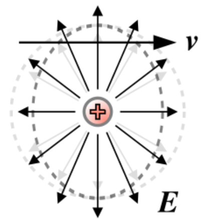
$$\left(-\frac{dE}{dx}\right)_{min} = 1\ - 2\ MeV g^{-1} cm^2 \quad for\ \ A > 1$$

at $\beta\gamma = 3 - 3.5$ *or* $T_{min} = 2.2 - 2.6\ m_0 c^2$

from C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016).

HEAVY CHARGED PARTICLES - STOPPING POWER IV



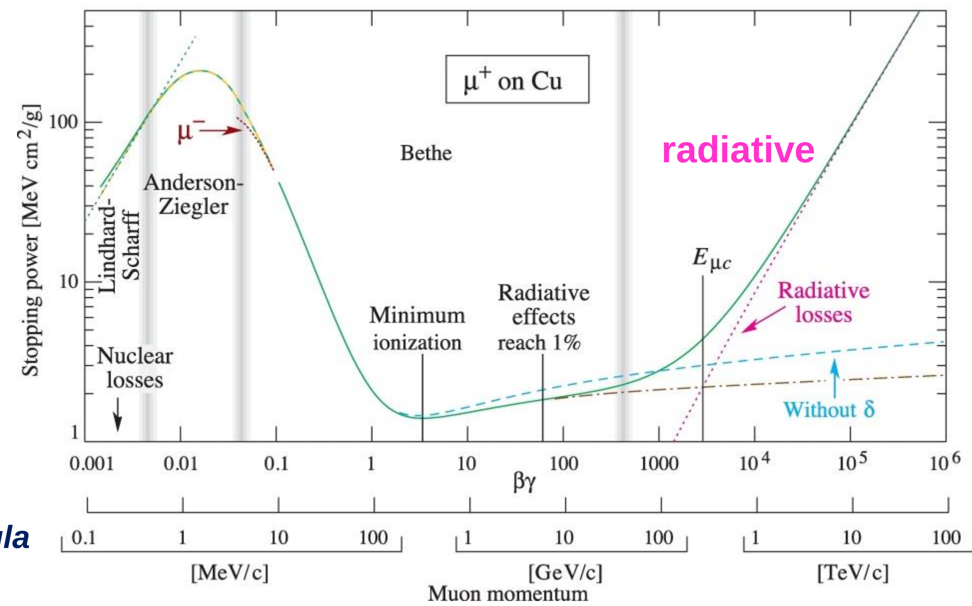


$$E_{\perp} = \gamma E_0$$
$$E_{\parallel} = E_0$$

„LHC“ range

radiative losses

- *bremsstrahlung*
- *pair production e^+e^-*
- *photonuclear*



δ density effect

polarization diminishes relativistic rise

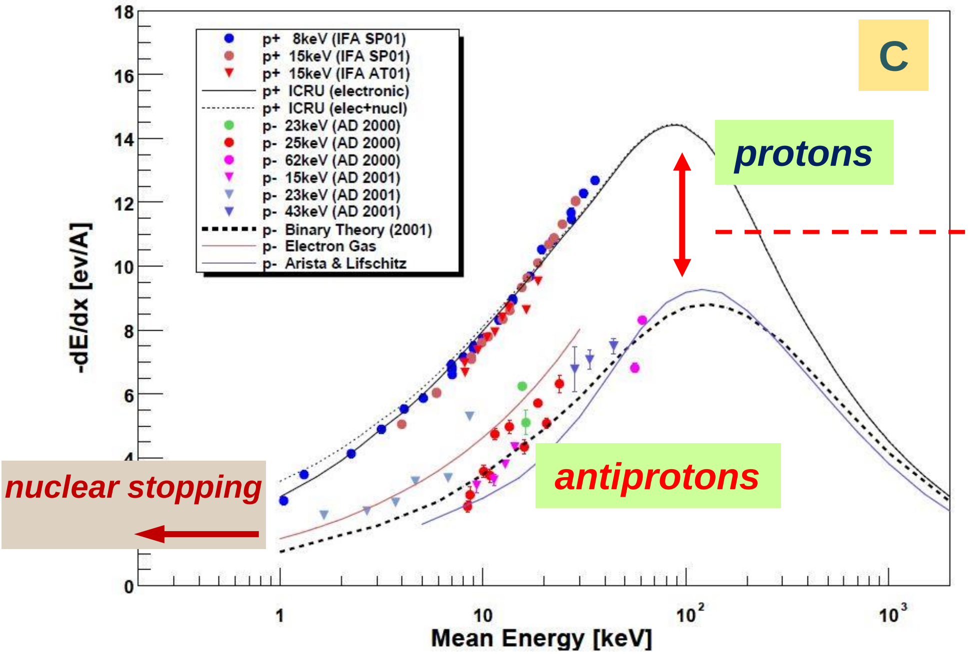
<u>not</u> covered by this formula

$$S = 4\pi N_A {r_e}^2 m_e c^2 \frac{Z_{target}}{A} \cdot \frac{z^2{}_{projectile}}{\beta^2} \cdot \left[\frac{1}{2} ln\left(\frac{2m_e c^2 \beta^2 \gamma^2 {T_e}^{max}}{I^2}\right) - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

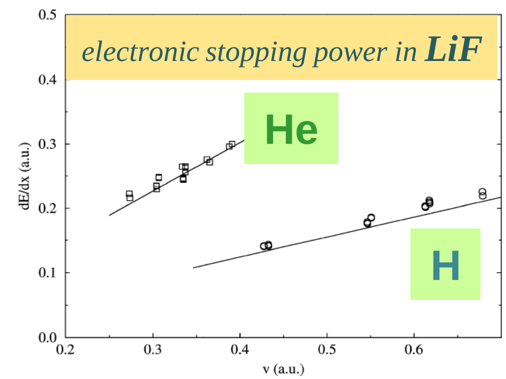
HEAVY CHARGED PARTICLES - BARKAS EFFECT

lowest energies - friction range

like friction $-\left(\frac{\Delta E}{\Delta x}\right) \propto \mathbf{v}$



A.Csete / PhD thesis, Aarhus, 2002



Juaristi et al, PRL 84, 2124 (2000)

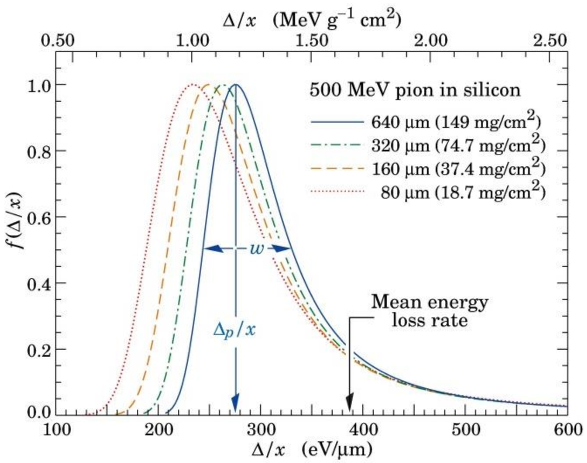
sensitive to sign of charge

$$S = 4\pi N_A {r_e}^2 m_e c^2 \frac{Z_{target}}{A} \cdot \frac{z^2_{projectile}}{\beta^2} \cdot \{[\ldots] + L_1(\beta, Z_{target}) \cdot z_{projectile}\}$$

frictional cooling (e-cooler, muon collider), window design, …

HEAVY CHARGED PARTICLES - STRAGGLING

energy (loss) straggling Δ



Landau-Vavilov distribution

asymmetric energy straggling towards higher Δ

thick layers → many collisions → skewness decreases

Δ_p/x *most probable energy loss (here normalized to unity)*

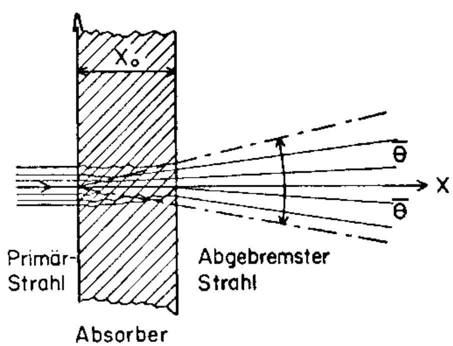
Δ/x *energy loss per layer thickness*

$$\overline{\Delta}^2 \propto \frac{Z}{A}\cdot\rho\cdot d\cdot\frac{1}{\beta^2}$$

for „thin" layers

from C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016).

angular straggling $\overline{\Theta}$



$$\overline{\Theta} = \frac{13.6\ MeV}{\beta cp}\sqrt{x/X_0}\,(1+\ldots) \propto z\cdot Z/p^2$$

many collisions → Gaussian angular distribution

X_0/gcm^{-2}	= 63 (126)	H_2 (D_2)	radiation length
	= 108	Si	
	= 13.8	Fe	

x/gcm^{-2} effective thickness of layer ($x = d\cdot\rho$)

- *acceptance of experimental setup (storage rings etc.)*
- *position resolution of tracking devices*

HEAVY CHARGED PARTICLES - RANGE I

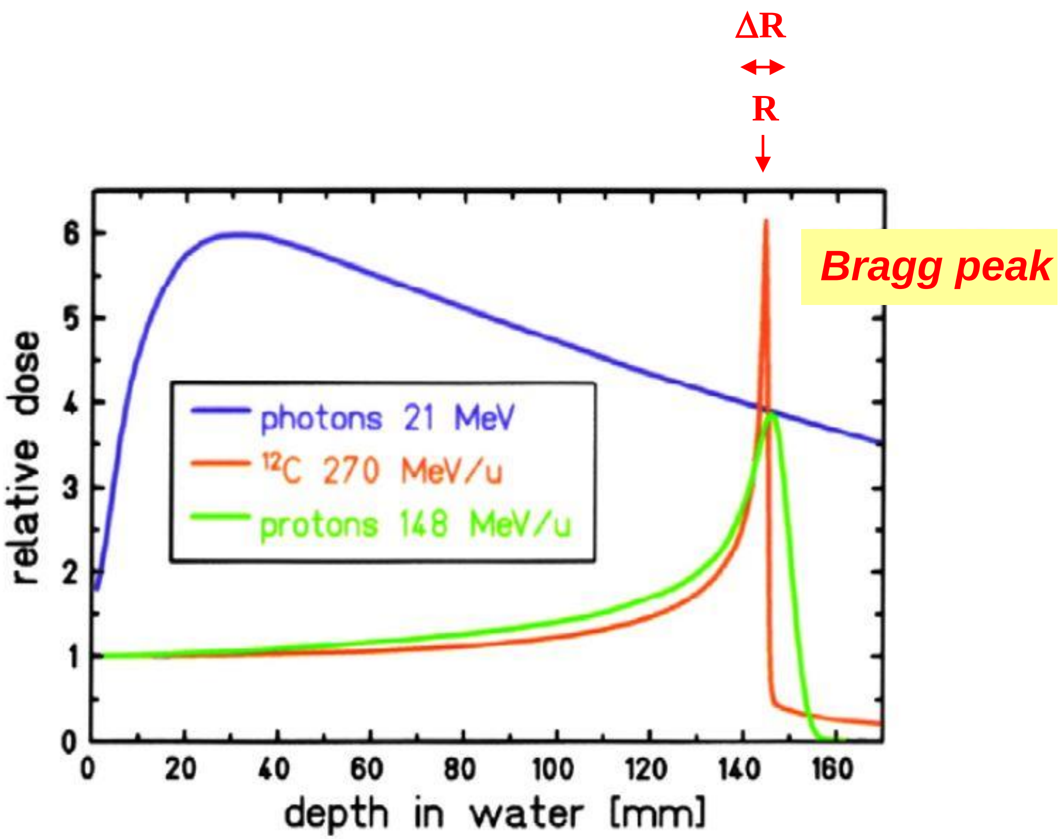


Fig. 1. Depth dose distribution for photons and monoenergetic Bragg curves for carbon ions and protons (Courtesy of G. Kraft, GSI Darmstadt, Germany).

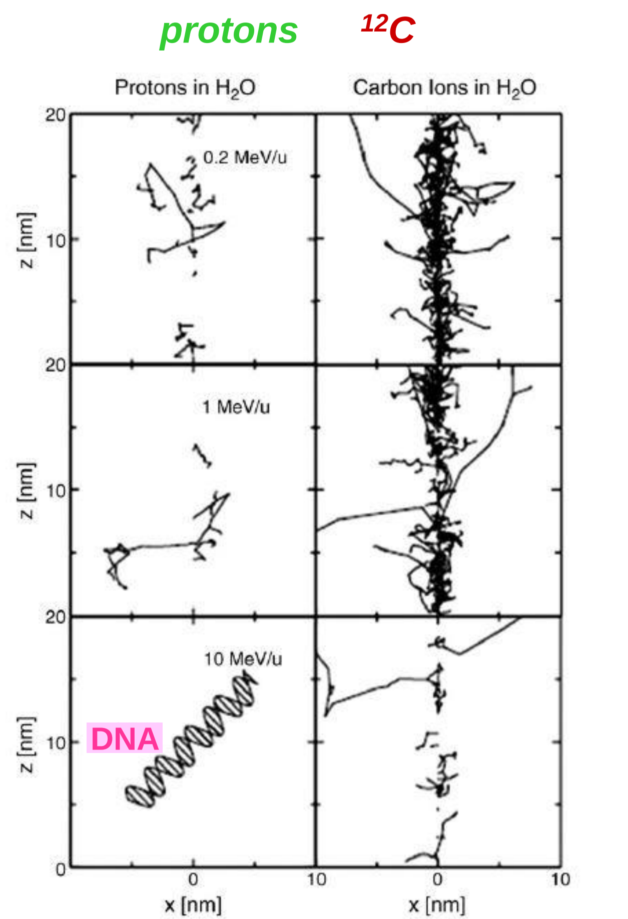


Fig. 4. Proton and carbon ion tracks are compared microscopically to an illustration of a DNA molecule before, in and behind the Bragg maximum, for the same energy [41].

Biochimica et Biophysica Acta 1796 (2009) 216–229

HEAVY CHARGED PARTICLES - RANGE II

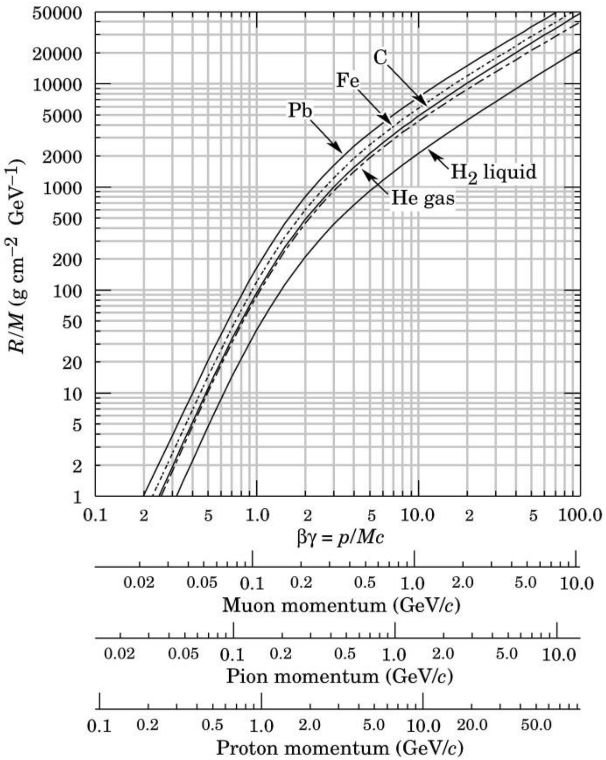
mean range $R = \int_{T_{kin}}^{0} dE / (dE/dx)$ [cm]

depends on particle mass

range – straggling ΔR

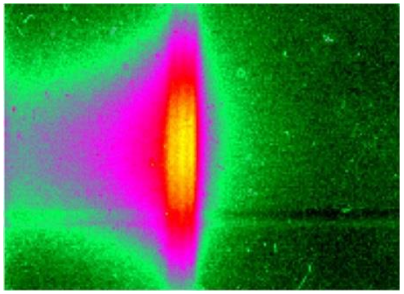
longitudinal $\Delta R / R$ $\approx$ *1% – 3%* *for all elements*

transversal $\approx$ *2% – 6%*



47 MeV antiprotons

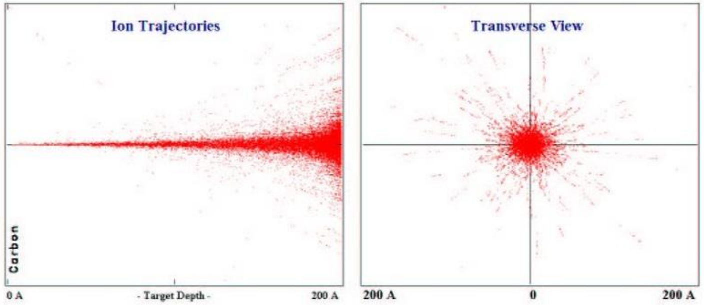
radiochromic film response



N. Bassler et al.
Radiotherapy and Oncology 86 (2008) 14–19

20 keV protons on carbon

(Monte-Carlo simulation SRIM)



A.Csete / PhD thesis, Aarhus, 2002

R/M(E/M)

range concept useful for

- $R < \lambda_{had}$

- radiation losses small

INTERACTION OF

LIGHT CHARGED PARTICLES

WITH MATTER

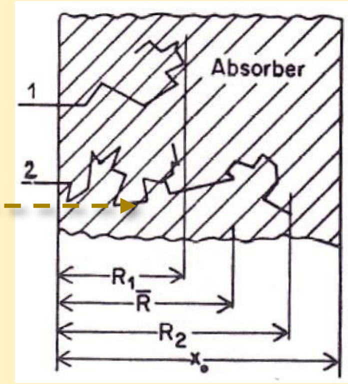
LIGHT CHARGED PARTICLES - STOPPING POWER

ionisation dominated energy range

heavy particles — path lengths **S ≈ range R**

electrons/positrons — " " **S ≈ 2 · R**

strong deflection



dE/dx similar to Bethe-Bloch formula

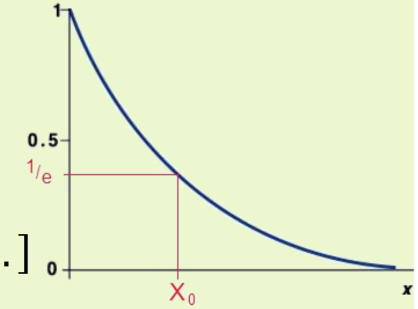
additional terms ***- identical particles (e^-)***
- spin dependence

radiation dominated energy range

energy loss by bremsstrahlung $-\frac{dE_{kin}}{dx} \propto Z^2{}_{target} \cdot E_{kin} \cdot [\ldots]$

$$\Rightarrow \quad E_{kin} = E_{0,\,kin} \cdot e^{-\left(x/X_0\right)}$$

radiation length X_0 **[g·cm^{-2}]** $\frac{1}{X_0} = 4\,\alpha \cdot r_e{}^2 \cdot \frac{N_A}{A} \cdot Z^2{}_{target} \cdot [\ldots]$



after depth d = X_0/ρ ([cm]) all but 1/e of the energy of the particle is lost by bremsstrahlung

LIGHT CHARGED PARTICLES - RANGE

ionisation dominated energy range

electron range ***(semiempirical formulae)***

$$R = 0{,}52\,E^{(MeV)} - 0{,}09 \quad (g\,cm^{-2}) \qquad 0{,}5 < E_e < 3\ MeV$$

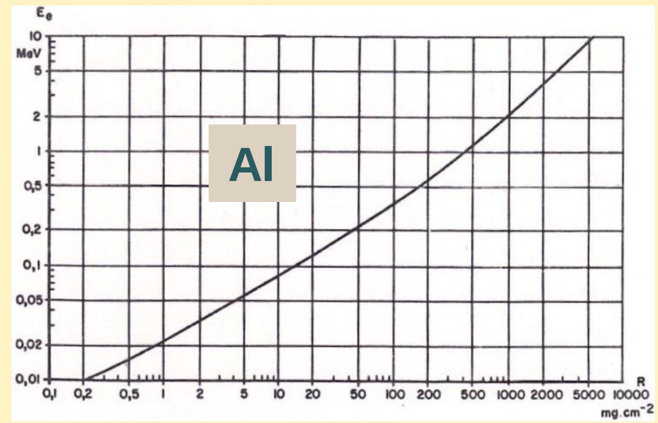
$$R = 0{,}412\,E^{n} \quad (g\,cm^{-2}) \qquad 0{,}01 < E_e < 3\ MeV$$

$$\text{mit} \quad n = 1{,}265 - 0{,}0954\,\ln E_e$$

$$R = 0{,}53\,E^{(MeV)} - 0{,}106 \quad (g\,cm^{-2}) \qquad 1 < E_e < 20\ MeV$$

$$-\frac{dE}{dx} = \frac{2\pi e^4}{E_e} N^{o} Z \left(\ln \frac{E_e}{I} + 0{,}15 \right) \qquad E_e \ll m_e c^2$$

$$-\frac{dE}{dx} = \frac{2\pi e^4}{m_e c^2} N^{o} Z \left(\ln \frac{E_e^3}{2 m_e c^2 I^2} + \frac{1}{8} \right) \qquad E_e \gg m_e c^2$$



radiation dominated energy range

radiation length X_0 [g·cm^{-2}]

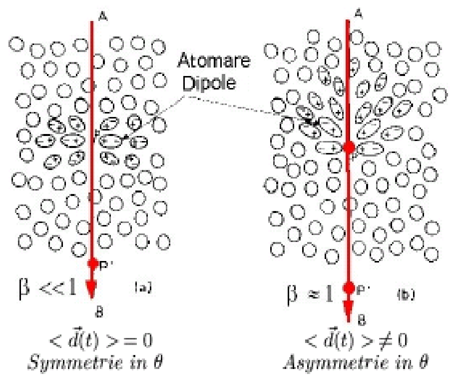
D_2	126	mylar	40
H_2	63	air	37
Al	24	water	36
Ar	20	rock standard	27
Cu	13	CsI	8.4
Pb	6	$PbWO_4$	7.4

CHARGED PARTICLES - ENERGY LOSS BY RADIATION I

Čerenkov radiation if $v_{particle} > c_{in\ medium}$

Čerenkov 1930s

the charge polarizes the medium

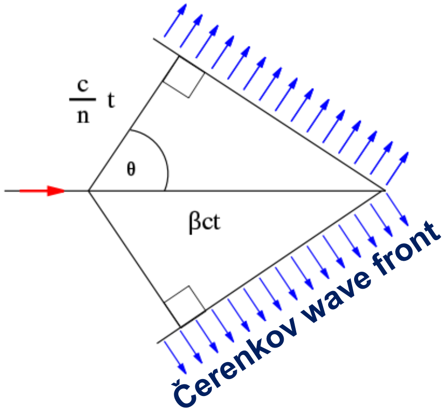


„light" blue!

electrons „radiate"
in the water above
the core of
a nuclear power plant

$$\left(\frac{\Delta E}{\Delta x}\right)_{\check{C}radiation} << \left(\frac{\Delta E}{\Delta x}\right)_{collision}$$

emission under specific angle $\Theta_{\check{C}}$



$\cos \Theta_{\check{C}} = 1 / \beta \cdot n$

n = index of refraction

(small) dispersion !

$\Theta_{\check{C}}$ measures the velocity of the particle

acoustics analogue: Mach's cone for supersonic source

CHARGED PARTICLES - ENERGY LOSS BY RADIATION II

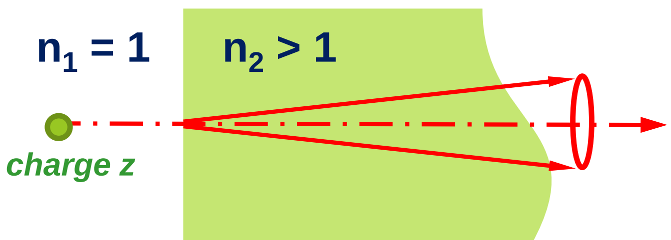
Transition radiation for ultrarelativistic particles (γ >> 1)

Ginzburg & Frank 1946

Readjustment of the el.-mag. fields (E,H) at the boundary of 2 media

with different dielectric properties (ε)

leads as collective response of the material to ***emission of el.-mag. radiation (X-rays)***

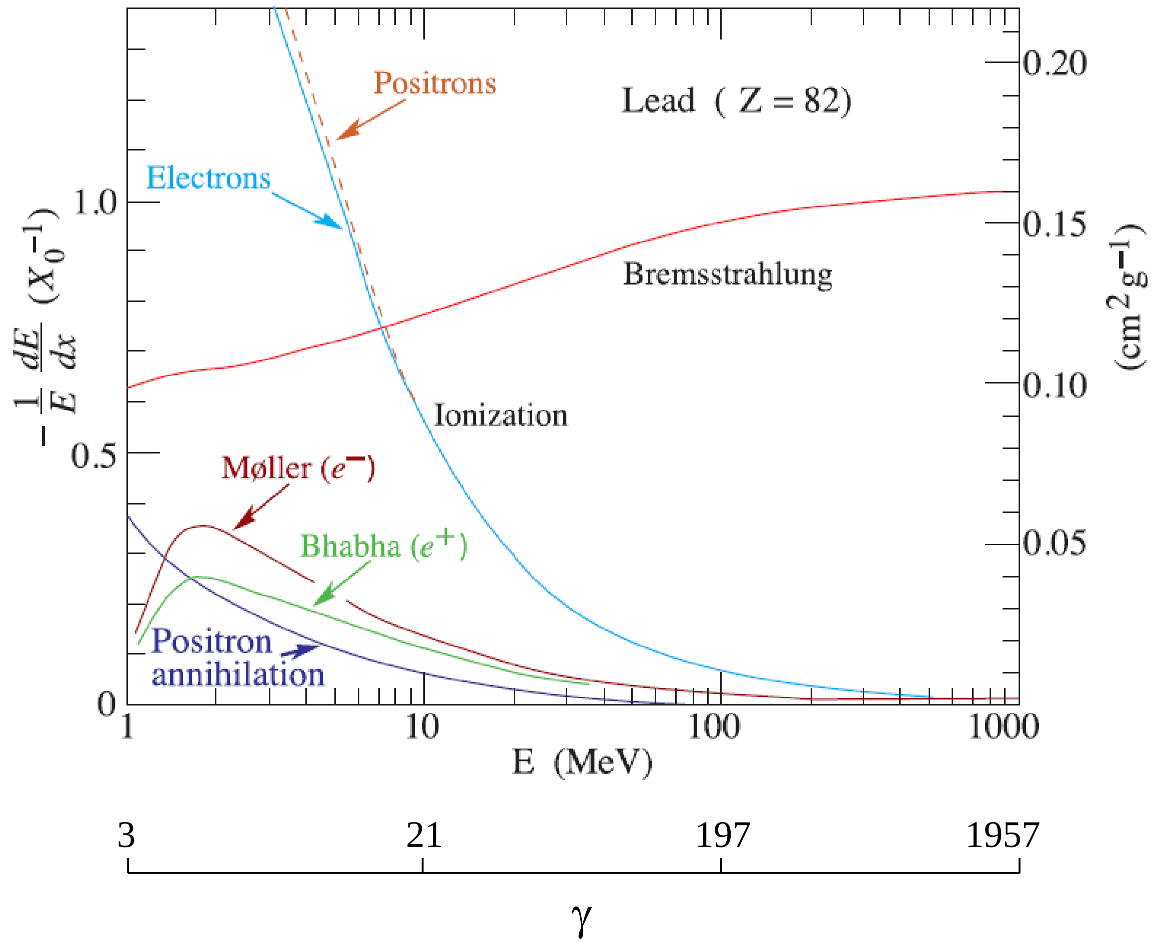


emission cone	$\Theta \approx 1/\gamma \approx 10^{-3}$ rad
radiated intensity	$I = \alpha \cdot z^2 \cdot \gamma \cdot \hbar\omega_P / 3$
photon yield	$n_{photon} \propto \alpha \cdot z^2 \cdot (\ln \gamma)^2 \approx z^2 \cdot 0.5\%$
plasma frequency	$\omega_P^2 = \frac{e^2}{\varepsilon_0} \cdot \frac{n_e}{m_e}$ $air: \hbar\omega_P = 0.7\ eV$ $mylar: \hbar\omega_P = 20\ eV$
formation length	$d = \frac{\gamma}{\sqrt{2}} \cdot \frac{\hbar c}{\hbar\omega_P}$ $mylar: d = 14\ \mu m\ (\gamma = 1000)$

typical: ***soft X-rays of 2 - 40 keV for $\gamma \approx 1000$***

application: plasma frequencies of materials, particle separation (π/p), …

LIGHT CHARGED PARTICLES - RELATIVE ENERGY LOSS



from
C. Patrignani *et al.*
(Particle Data Group),
Chin. Phys. C, **40**, 100001 (2016).

Fractional energy loss per radiation length in lead as a function of electron or positron energy.

INTERACTION OF

MASSIVE NEUTRAL PARTICLES

WITH MATTER

NEUTRONS I

collisions create recoil particles

maximum energy transfer for $M_{neutral} = M_{recoil}$

central collision	*energy is transferred completely*
non central	*all energies according to scattering angle*
averge energy transfer	*50%*

detection by recoil protons (from hydrogen)

$$M_{proton} \approx M_{neutron}$$

i.e. ***good shielding is water - H_2O***

concrete - 15% water

paraffin - $(CH)_n$

…

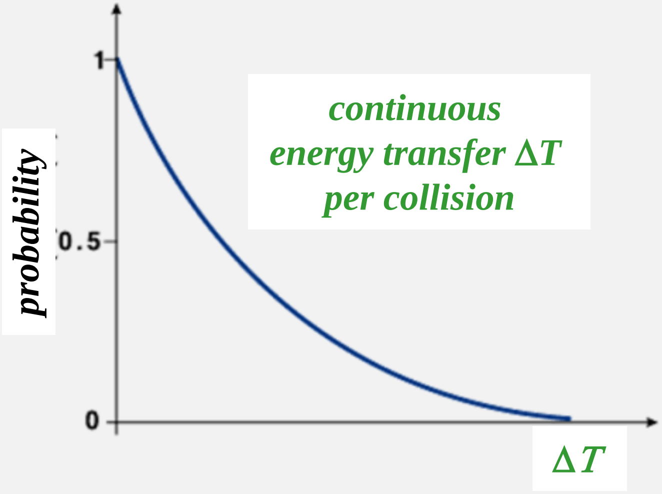
NEUTRONS II

slowing down of neutrons in elastic collisions

$$\left(\frac{A-1}{A+1}\right)^2 \cdot T_n \leq T_{n'} \leq T_n$$

T_n initial kinetic energy

T_n' kinetic energy after collision



neutrons – no defined range

make degrader thick enough to themalize neutrons, i.e. $T_n \approx \frac{1}{40}\ eV$

subsequent capture or decay

don't forget absorber for reaction and decay products (mostly γ)

SYNOPSIS:

BASIC INTERACTIONS ARE

BASIS FOR DETECTOR DESIGN