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JÜLICH FORSCHUNGSZENTRUM

Lecture B3

INTERACTION of PARTICLES with MATTER

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"Autumn Lectures" – Nuclear and Medical Physics

Tbilisi, Georgian Technical University (GTU)

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OVERVIEW

CHARGED PARTICLES : ENERGY LOSS BY IONIZATION

HEAVY CHARGED PARTICLES

LIGHT CHARGED PARTICLES

CHARGED PARTICLES : ENERGY LOSS BY RADIATION

NEUTRONS

PARTICLES - HEAVY or LIGHT

interaction happens by collisions of particles type 1 and 2

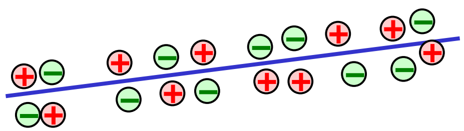
		before	after collision
1.	$M_{particle\ 1} >> M_{particle\ 2}$		
2.	$M_{particle\ 1} = M_{particle\ 2}$	 	

CHARGED PARTICLES - ENERGY LOSS BY IONIZATION

collisions create electron- ion pairs

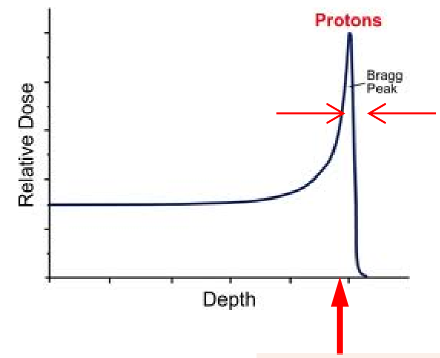
1. ***heavy*** **$M_{particle}$ >> $M_{electron}$**

e.g. protons, deuterons, …



strongly ionising

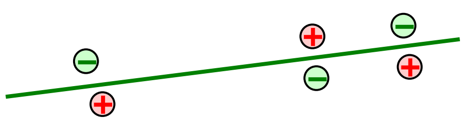
Bragg peak



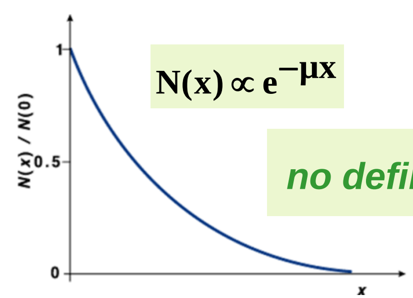
well defined range R!

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

HEAVY CHARGED PARTICLES - STOPPING POWER I

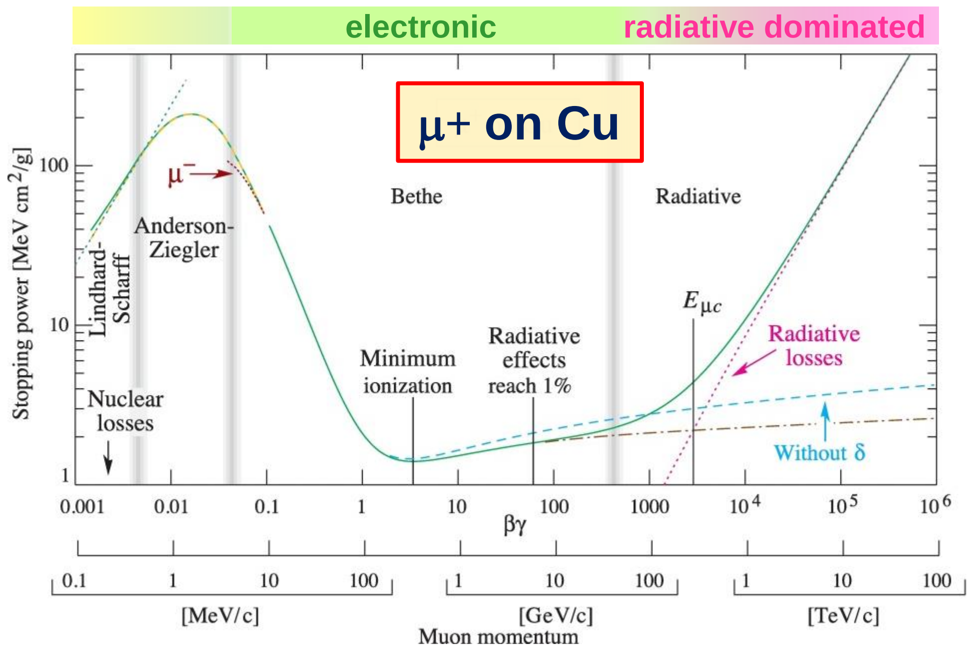
heavy particles ***μ, π, K, p, d, …***

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

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

$\beta = 0.7$

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



stopping power

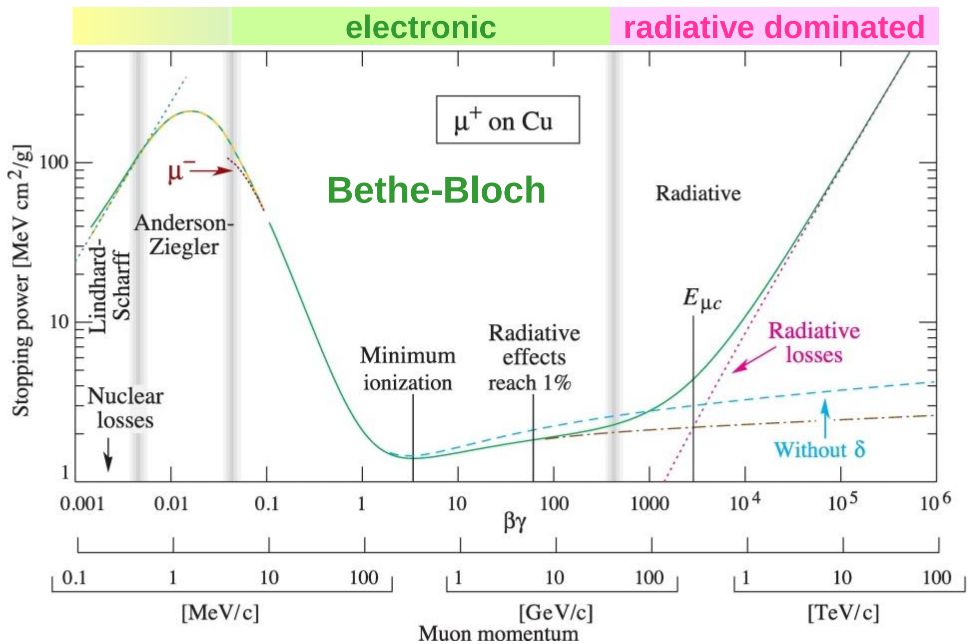
$$S = \left(-\frac{dE}{dx}\right) \cdot \frac{1}{\rho}$$

$[\text{MeV} \cdot \text{cm}^2/\text{g}]$

HEAVY CHARGED PARTICLES - STOPPING POWER I

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 II

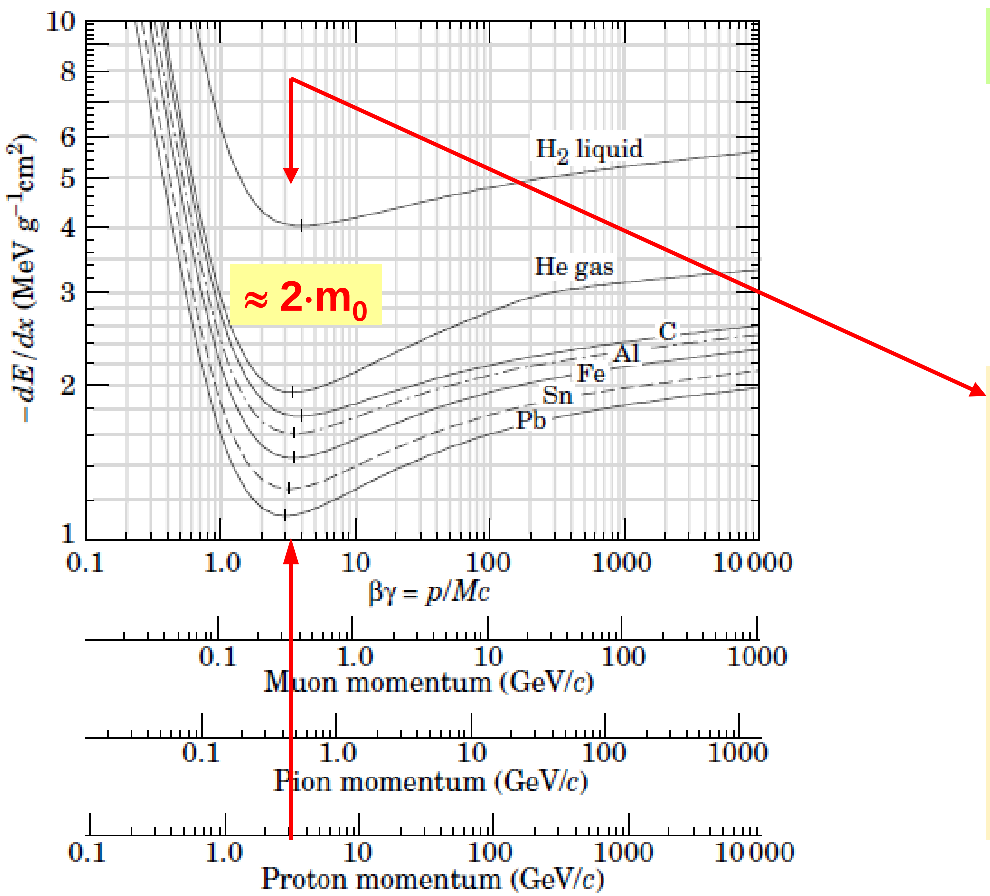


Figure 30.2: Mean energy loss rate in liquid (bubble chamber) hydrogen, gaseous helium, carbon, aluminum, iron, tin, and lead. Radiative effects, relevant for muons and pions, are not included. These become significant for muons in iron for $\beta\gamma \gtrsim 1000$, and at lower momenta for muons in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

Bethe-Bloch range

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

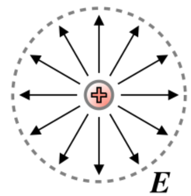
MIPs = *minimum ionising particles*

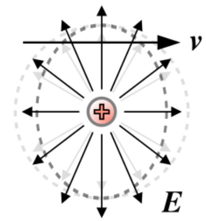
$$\left(-\frac{dE}{dx}\right)_{min} = 4\ MeV\,g^{-1}cm^2 \qquad \textit{for } A = 1$$

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

at $\beta\gamma = 3 - 3.5$ *or* $T_{min} = 2.2 - 2.6\ m_0c^2$

HEAVY CHARGED PARTICLES - STOPPING POWER III





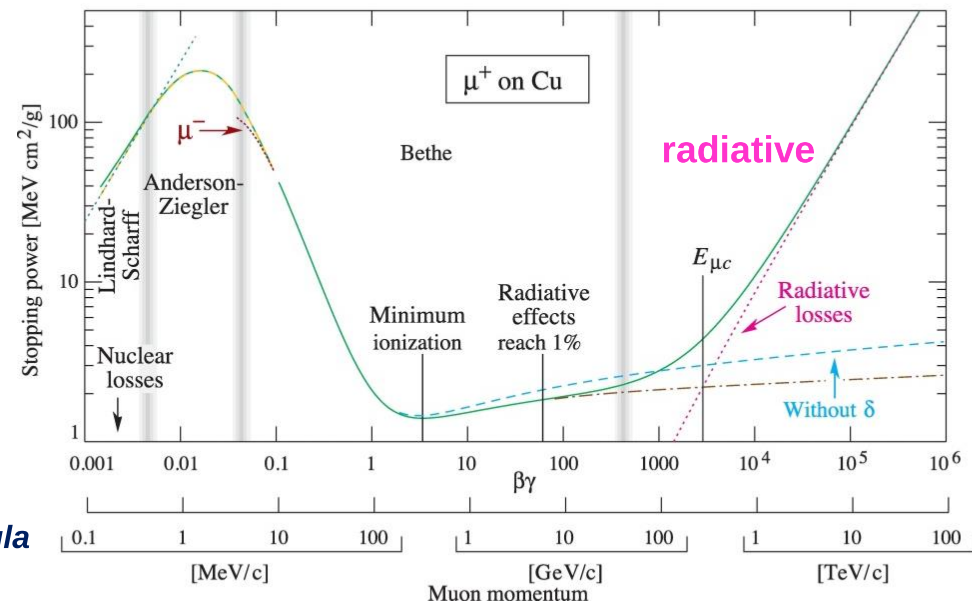
$$E_\perp = \gamma E_0$$
$$E_\parallel = E_0$$

„LHC“ range

radiative losses

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

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

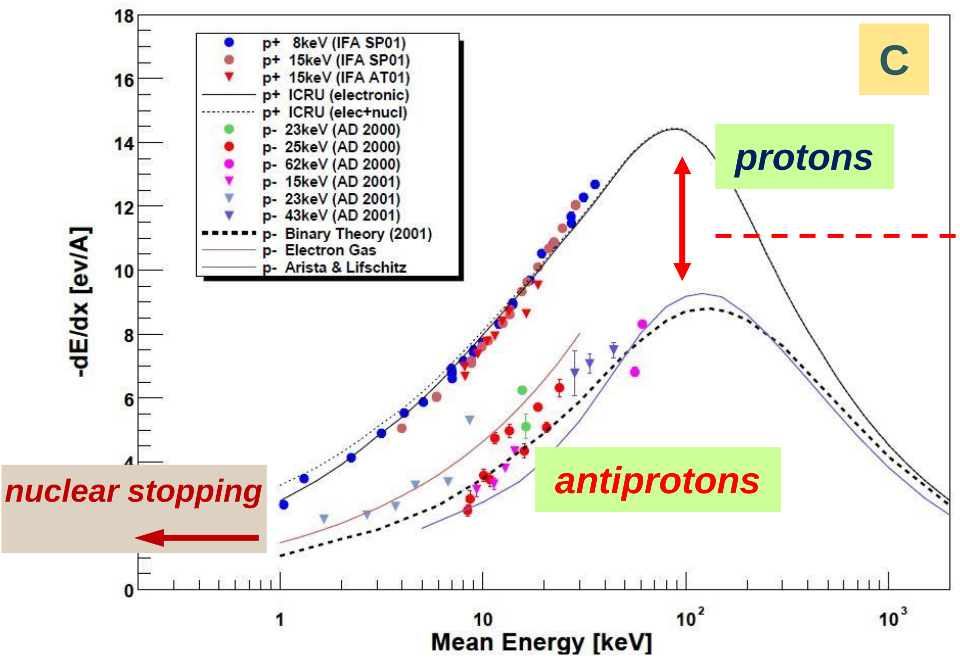


δ density effect

polarization diminishs relativistic rise

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

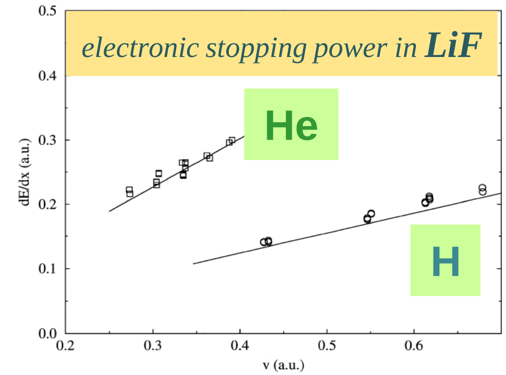
HEAVY CHARGED PARTICLES - BARKAS EFFECT



A.Csete / PhD thesis, Aarhus, 2002

lowest energies - friction range

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



Juaristi et al, PRL 84, 2124 (2000)

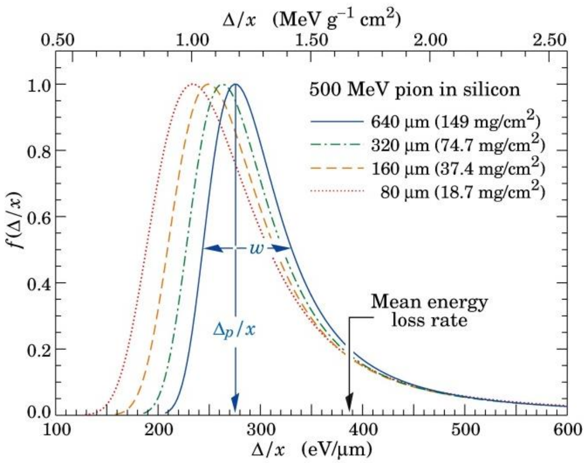
sensitive to sign of charge

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

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

HEAVY CHARGED PARTICLES : STRAGGLING

energy straggling



Landau-Vavilov distribution

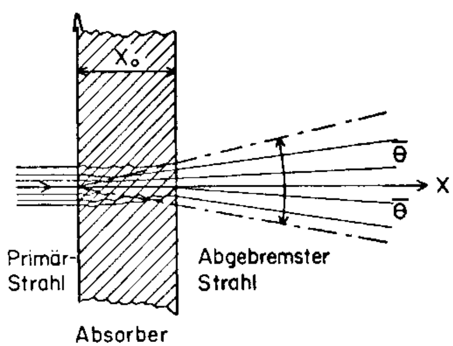
asymmetric energy straggling towards higher ΔE

thick layers → many collisions → skewness decreases

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

Δ/x *energy loss per layer thickness*

angular straggling



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

many collisions → Gaussian angular distribution

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

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

HEAVY CHARGED PARTICLES : RANGE I

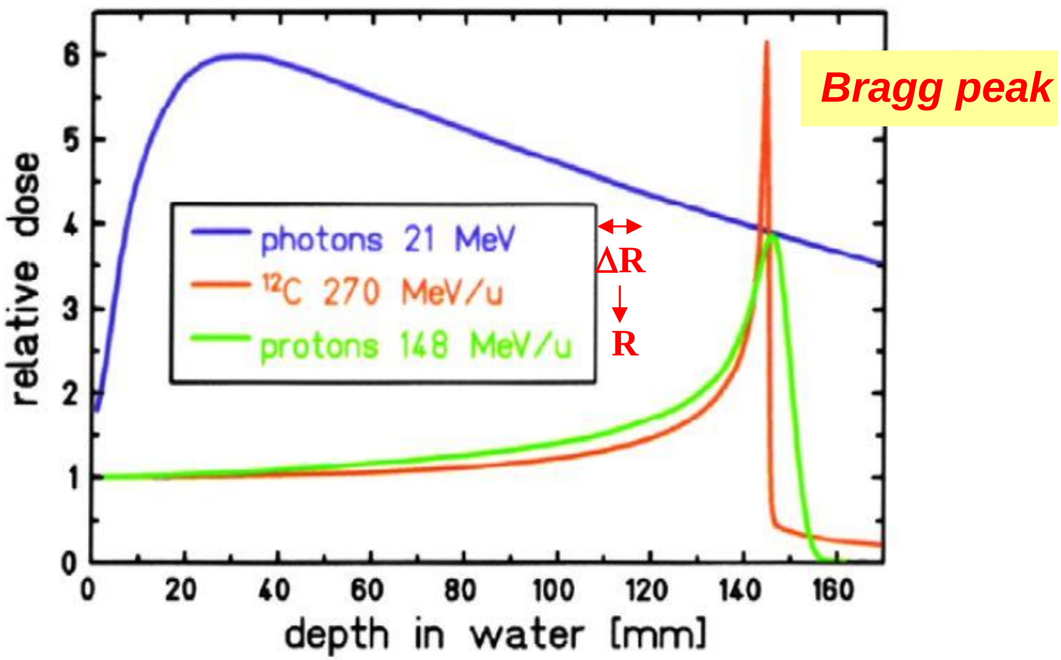


Fig. 1. Depth dose distribution for photons and monoenergetic Bragg curves for carbon ions and protons (Courtesy of G. Kraft, GSI Darmstadt, Germany).

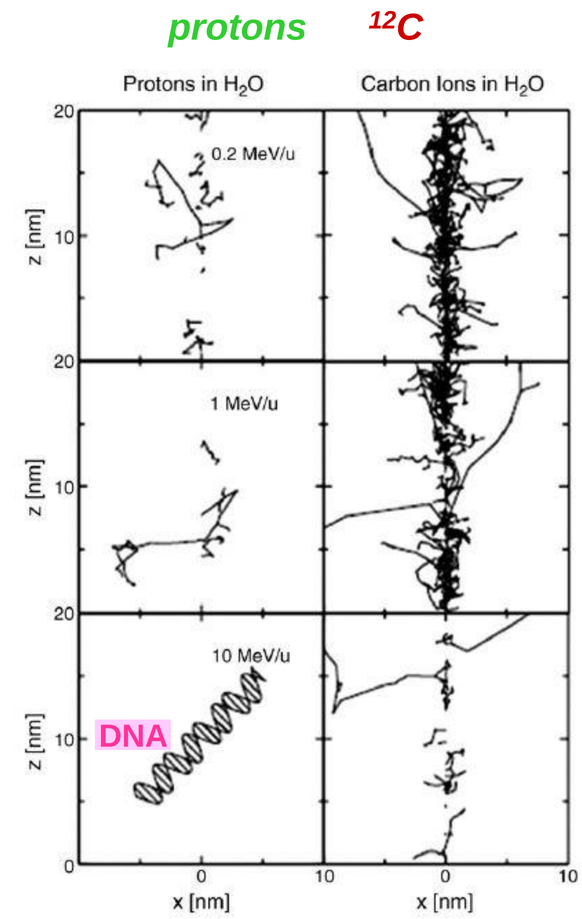


Fig. 4. Proton and carbon ion tracks are compared microscopically to an illustration of a DNA molecule before, in and behind the Bragg maximum, for the same energy [41].

Biochimica et Biophysica Acta 1796 (2009) 216–229

HEAVY CHARGED PARTICLES : RANGE II

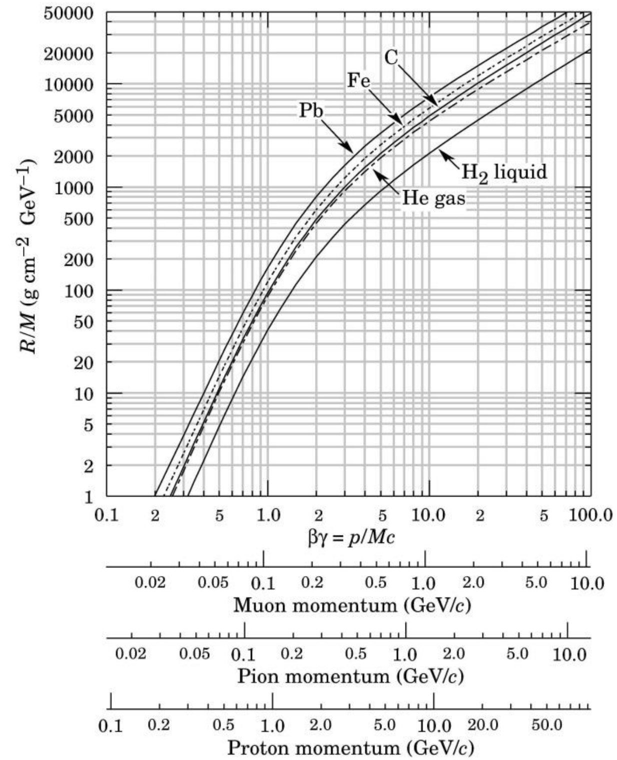
mean range $R = \int_{T_{kin}}^{0} dE / (dE/dx)$ [cm]

depends on particle mass

range – straggling ΔR

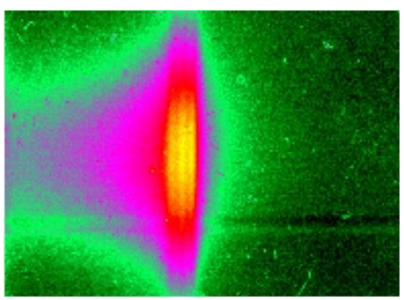
longitudinal $\Delta R / R$ *≈ 1% – 3%* *for all elements*

transversal *≈ 2% – 6%*



47 MeV antiprotons

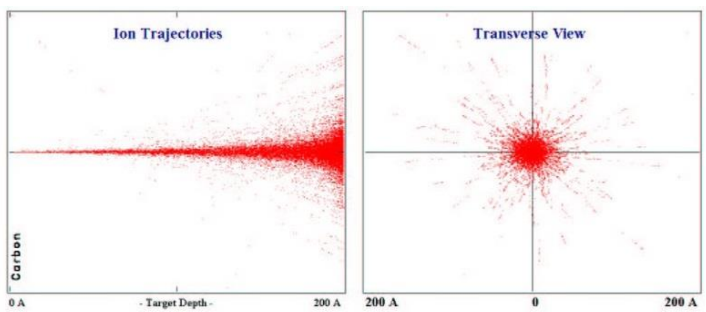
radiochromic film response



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

- $R < \lambda_{had}$

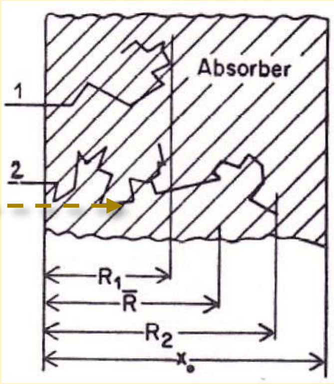
- radiation losses small

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

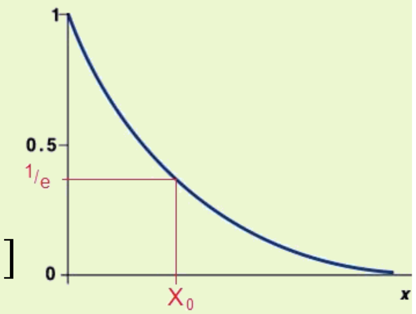
energy loss by bremsstrahlung

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

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

radiation length X_0 **[g·cm²]**

$$\frac{1}{X_0} = 4\alpha \cdot r_e{}^2 \cdot \frac{N_A}{A} \cdot Z^2{}_{target} \cdot [\ldots]$$



after depth ρ·X₀ ([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)*

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

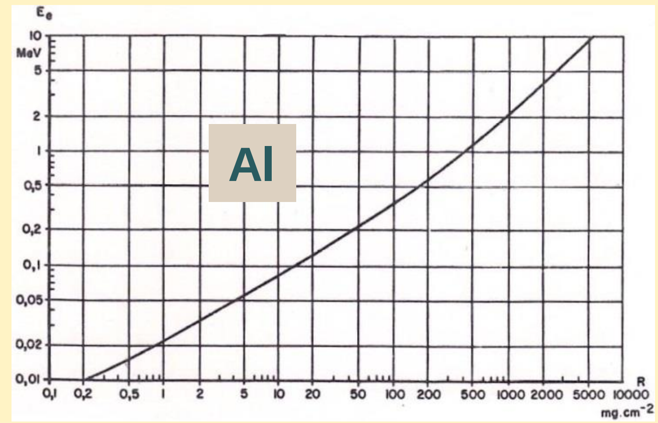
$$R = 0{,}412\, E^{n} \quad (g\, cm^{-2}) \qquad 0{,}01 < E_e < 3\ MeV$$

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

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

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

$$-\frac{dE}{dx} = \frac{2\pi e^4}{m_e c^2} N^0 Z \left(\ln \frac{E_e^3}{2 m_e c^2 I^2} + \frac{1}{8} \right) \qquad E_e \gg m_e c^2$$

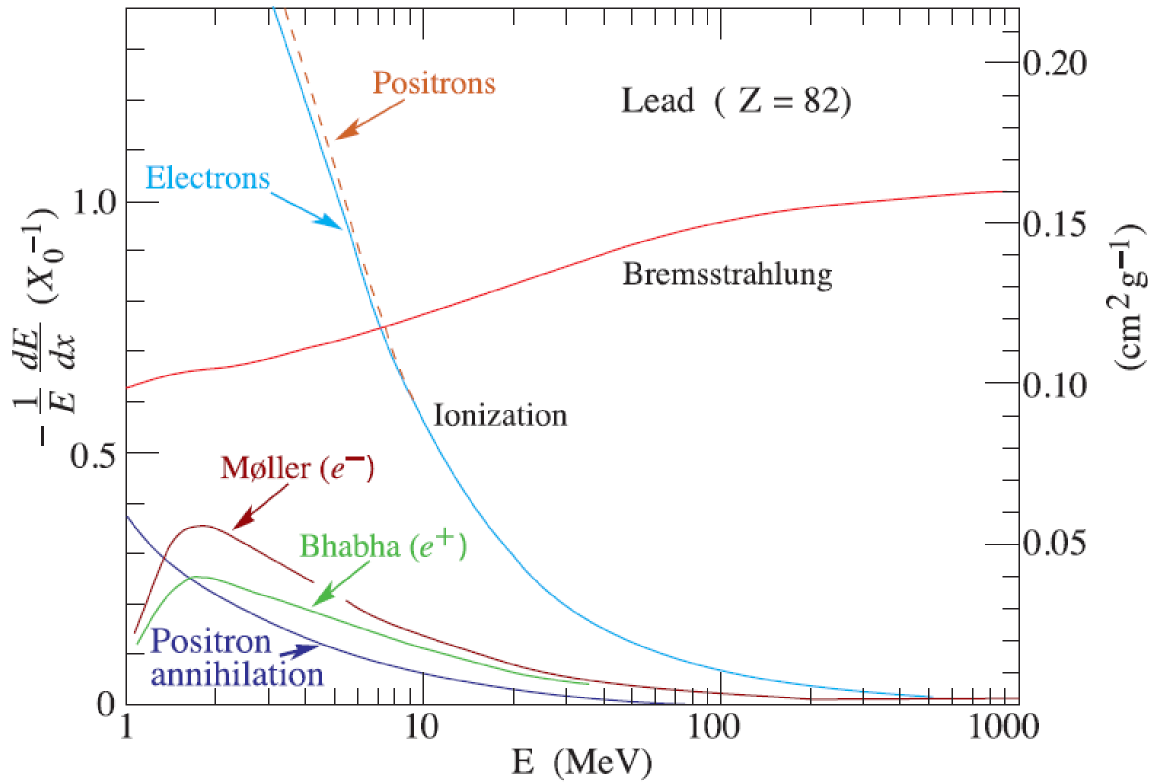


radiation dominated energy range

radiation length X_0 [g·cm²]

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

LIGHT CHARGED PARTICLES : RELATIVE ENERGY LOSS



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

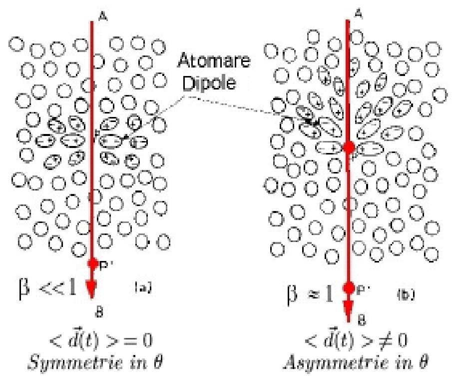
CHARGED PARTICLES: ENERY LOSS BY RADIATION I

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

Cerenkov 1930s

„light" blue!

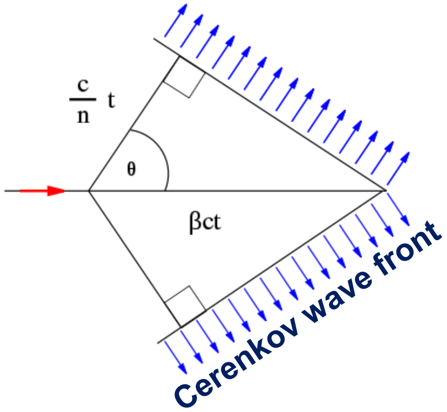
the charge polarizes the medium



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

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

emission under specific angle Θ_C



$\cos \Theta_C = 1 / \beta \cdot n$

n = index of refraction

(small) dispersion !

Θ_C measures the velocity of the particle

acoustics analogue: Mach's cone for supersonic source

CHARGED PARTICLES: ENERY LOSS BY RADIATION II

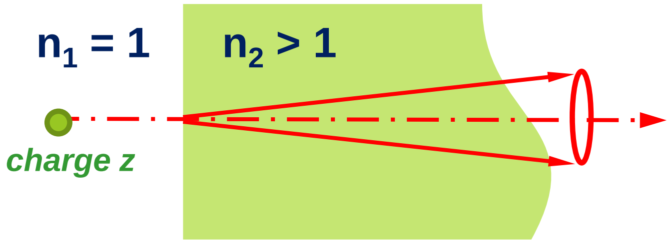
Transition radiation for ultrarelativistic particles ($\gamma \gg 1$)

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), …

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 shieldings are water***

concrete (15% water)

paraffin ($(CH)_n$)

…

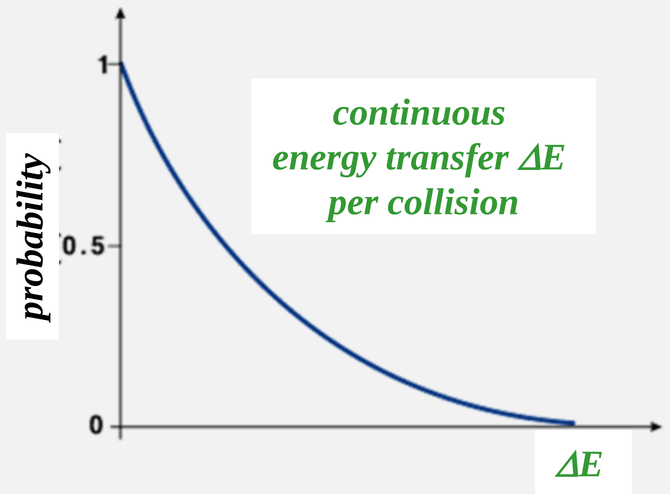
NEUTRONS II

slowing down of neutrons in elastic collisions

$$\left(\frac{A-1}{A+1}\right)^2 \cdot Tn \le Tn' \le Tn$$

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)