Plan of lectures:

- **Lecture #1 :** Introduction & interaction of heavy charged particles with matter
- **Lecture #2 :** Stopping of electrons in matter & photon interactions
- **Lecture #3 :** Neutron, hadron and neutrino interactions with matter

Lecture #1 Introduction & Interaction of heavy charged particles with matter

Reference books:

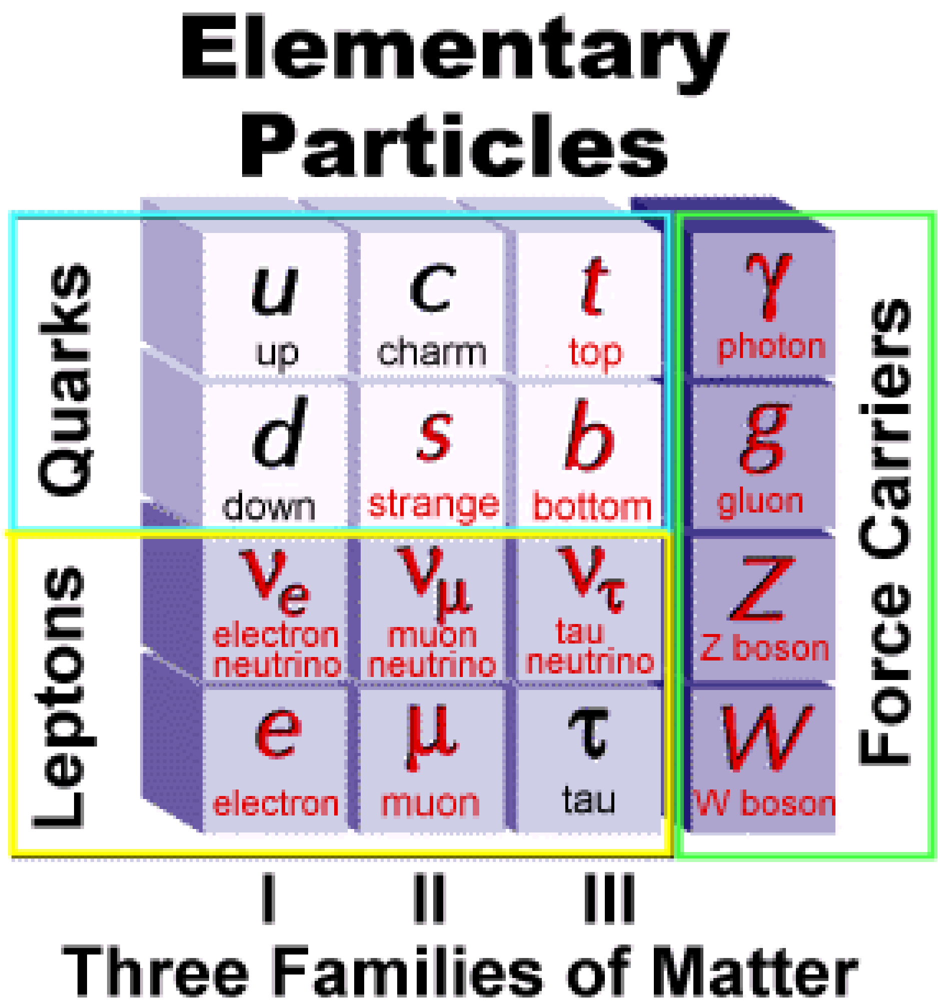
1. Techniques in nuclear & particle physics, W.R. Leo (2nd ed.)
2. Radiation Detection & measurement, G. Knoll (3rd ed.)
3. Introduction to experimental particle physics, R.C. Fernow (CUP 1989)
4. Experimental techniques in HEP, T. Ferbel (ed) (World Scientific 1991)

Journals, Handbooks, Web resources:

- Nuclear Instruments & Methods
- IEEE (Nucl. Sc.)
- Reports on Progress in Physics
- Annual Reviews in Particle & Nuclear Science
- Proceedings of various Detector Conferences
- Particle Data Group handbook (Phys. Rev. D/Phys. Lett./J.Phys G)
- CERN E-resources (Yellow books)

What are the particles we deal with?

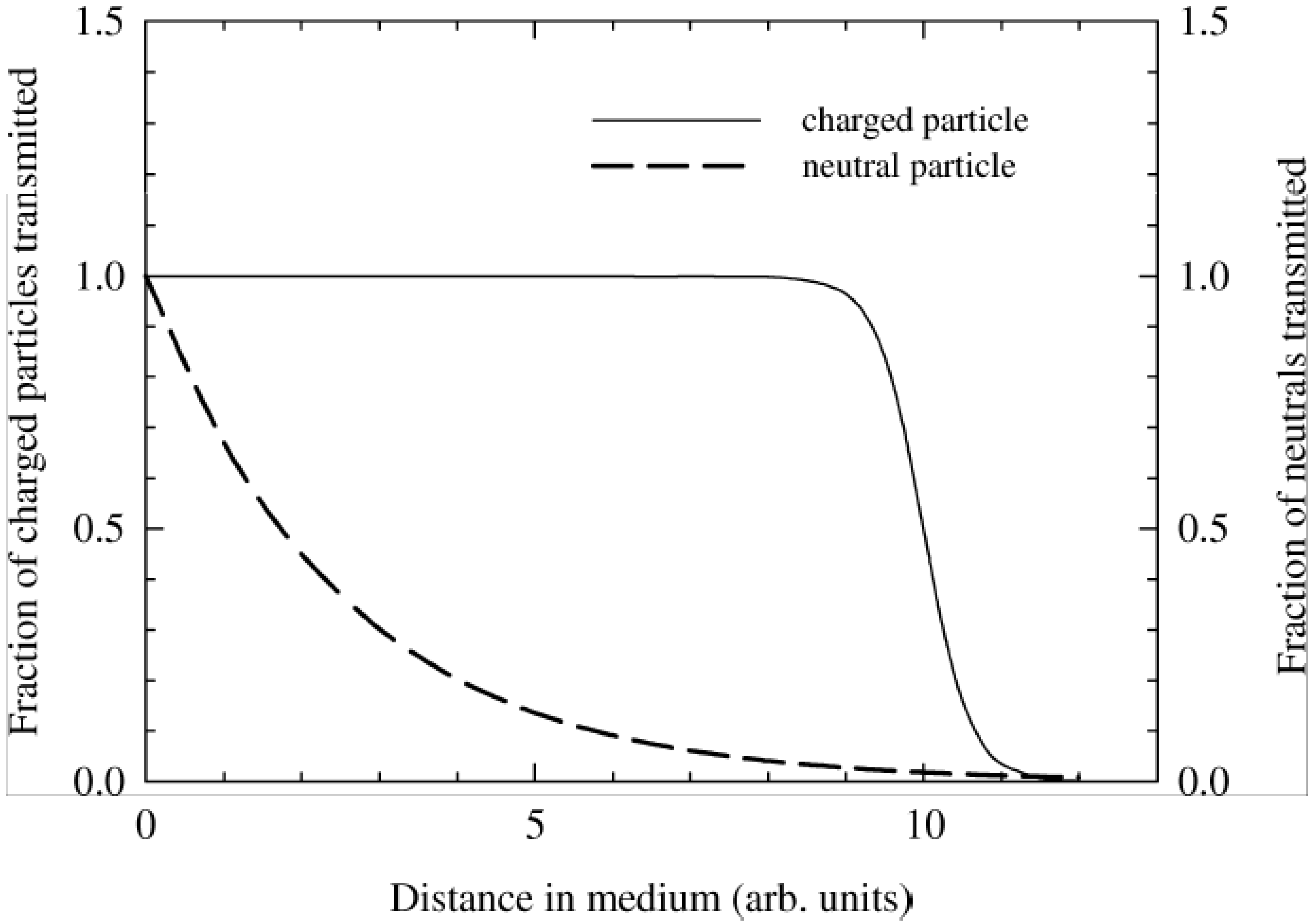
- Hadrons (p, n, π, K, Λ, J/Ψ …) : composites of quarks and nuclei (heavy ions)
- Leptons (e, μ, τ, corresponding νs)
- Bosons (force carriers) such as **γ, W$^{\pm}$, Z**



p (uud), *n* (udd)

From SLAC website - http://www2.slac.stanford.edu/vvc/theory/fundamental.html

Penetration of charged & neutral particles in matter

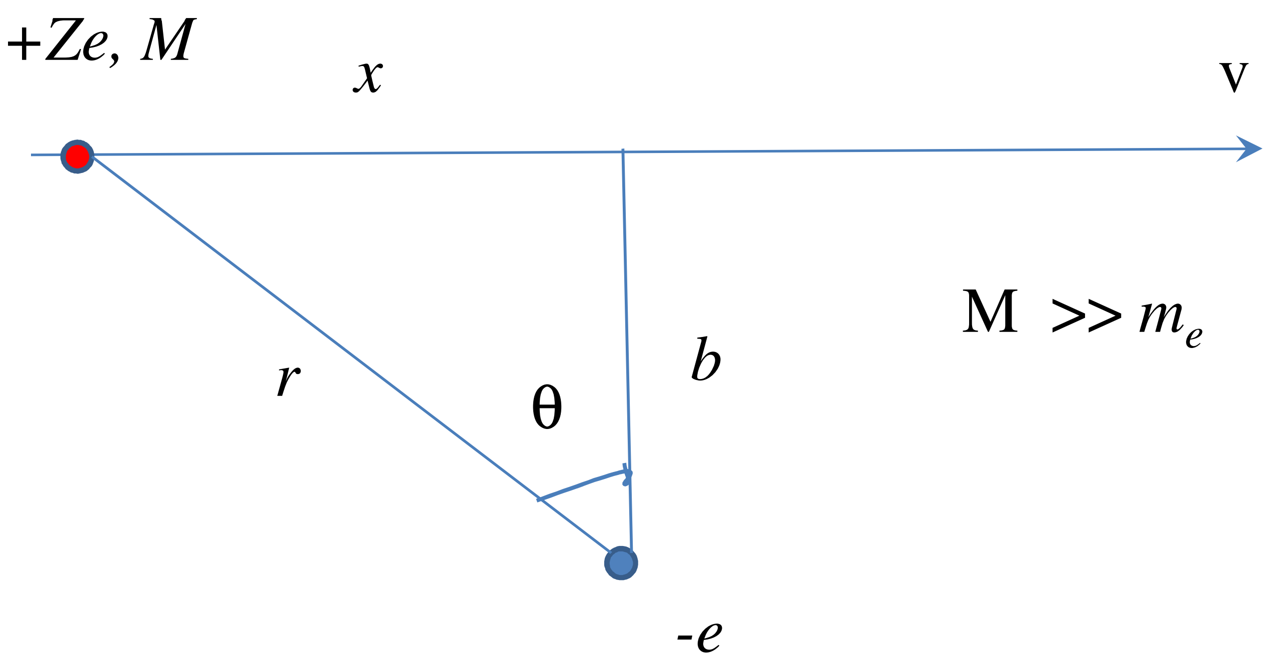


Lecture#2 Interaction of heavy charged particles with matter

Heavy charged projectile loses energy to electrons in medium

since $m_e << M_{nucl}$. Assume first interaction with electron at rest.

Semi-classical approach (Bohr 1915, 1948)



$M >> m_e$

Bohr calculation assumes independent collisions, disordered medium. Latter not valid in crystalline medium along certain directions (channelling!).

Typical energy lost in single collision ~ 1-100 eV for 10 MeV proton

Interaction cross section of unit elecrric charged projectile with atom ~ 10^{-17} cm^2

$$\Delta p = \int^{-\infty}_{+\infty} F_{\perp}\, dt$$

$$= \int^{-\infty}_{+\infty} Ze^2/(b/\cos\theta)^2 .\cos\theta\, dx/v$$

$$= Ze/(bv) .[\sin\theta]^{\pi/2}_{-\pi/2}$$

$$\Delta E = (\Delta p)^2/2m_e = 4Z^2e^4/(b^2v^2) . 1/2m_e$$

For a range of impact parameters, b to b+db, distance travelled = Δx, # density of electrons in medium = n_e , energy loss given by

$$\Delta E(b) = \Delta E .n_e\, 2\pi b db\, \Delta x = 2Z^2e^4/(m_e v^2 b^2) .n_e\, 2\pi b db\, \Delta x$$

$$\Delta E/\Delta x = 4\pi n_e Z^2 e^4/ (m_e v^2) \int^{bmax}_{bmin} db/b$$

$$= 4\pi n_e Z^2 e^4/ (m_e v^2) . ln\, (b_{max}/b_{min})$$

Here b_{min}, b_{max} can be estimated from semi-classical considerations

1. Upper limit b_{max} :

Min. kinetic energy transferred to target electron $T_e \sim I\ (=BE_e) \sim \hbar\omega$

$\omega = \gamma / (b_{max}/v_p) \Rightarrow b_{max} = \gamma v_p \hbar / I$

2. Lower limit b_{min} :

Max. KE of electron from target $T_e = 4 . \frac{1}{2} m_e v^2$

and in relativistic kinematics $2\gamma^2 m_e v^2 = 2Z^2 e^4 / (m_e v_p^2 b_{min}^2)$

so that $b_{min} = Ze^2 / (\gamma m_e v_p^2)$

From QM consideration, using Heisenberg uncertainty principle,

$\Delta p \, . \, b_{min} \sim \hbar \Rightarrow b_{min} \sim \hbar / (\gamma m_p v_p)$

$$S_e\,(\text{Bohr}) = 4\pi n_e Z^2 e^4 / (m_e v^2)$$

$$= 2\pi n_e M_p Z_p^{\,2} e^4 / E_p \;.\; ln\,[\beta\gamma m_e v_p^{\,2}\, \hbar c/(I_e Z_p e^2)]$$

$$S_e\,(\text{QM}) = 2\pi n_e M_p Z_p^{\,2} e^4 / E_p \;.\; ln\,[\gamma^2 m_p v_p^{\,2}/I_e]$$

Fully QM treatment of Bethe and Bloch + density effect and shell correction gives

$$S_e\,(\text{QM}) = 4\pi N_A\, r_e^{\,2}\, m_e c^2\, \rho_T\, (Z_T/A_T)\, Z_p^{\,2}/\beta^2$$

$$.\,[1/2\; ln\,(2 m_e \gamma_p^2\, v^2 W_{max}/I) - \beta^2 - \delta/2 - C/Z_T]$$

Where $r_e = e^2/m_e c^2$, N_A = Avogadro's no., ρ_T = target density,

$$W_{max} = 2 m_e c^2 \gamma^2 \beta^2 / [1 + 2\,\gamma m_e/M + (m_e/M)^2]$$

δ = density effect factor, C = atomic shell effect parameter

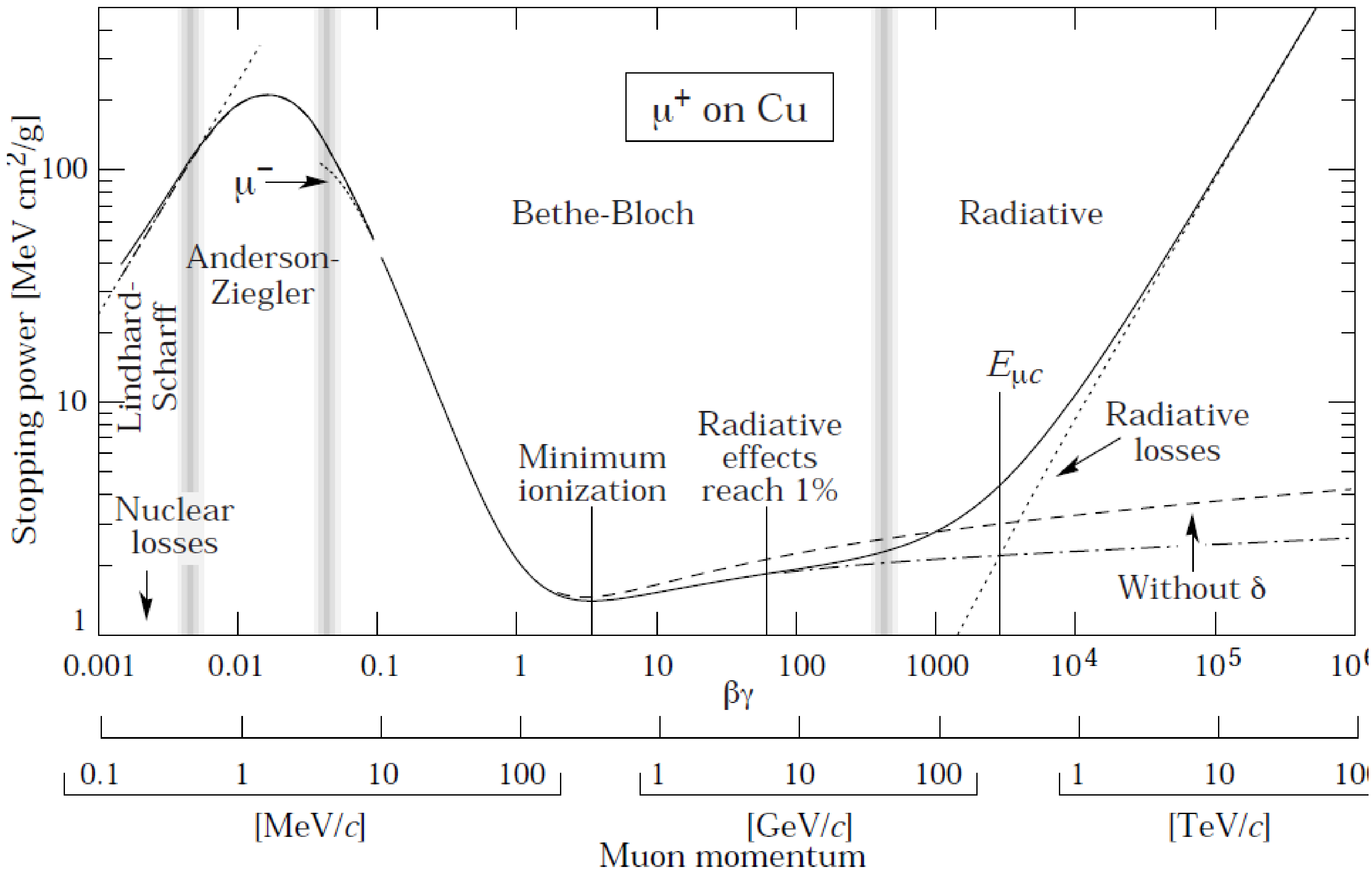
Density effect arises from polarization of medium induced by the projectile charge which in turn shields its field and reduces effect on “far” electrons ⇒ reduction in stopping power

References

J.D. Jackson, Classical Electrodynamics 3rd ed. (Wiley 2001)

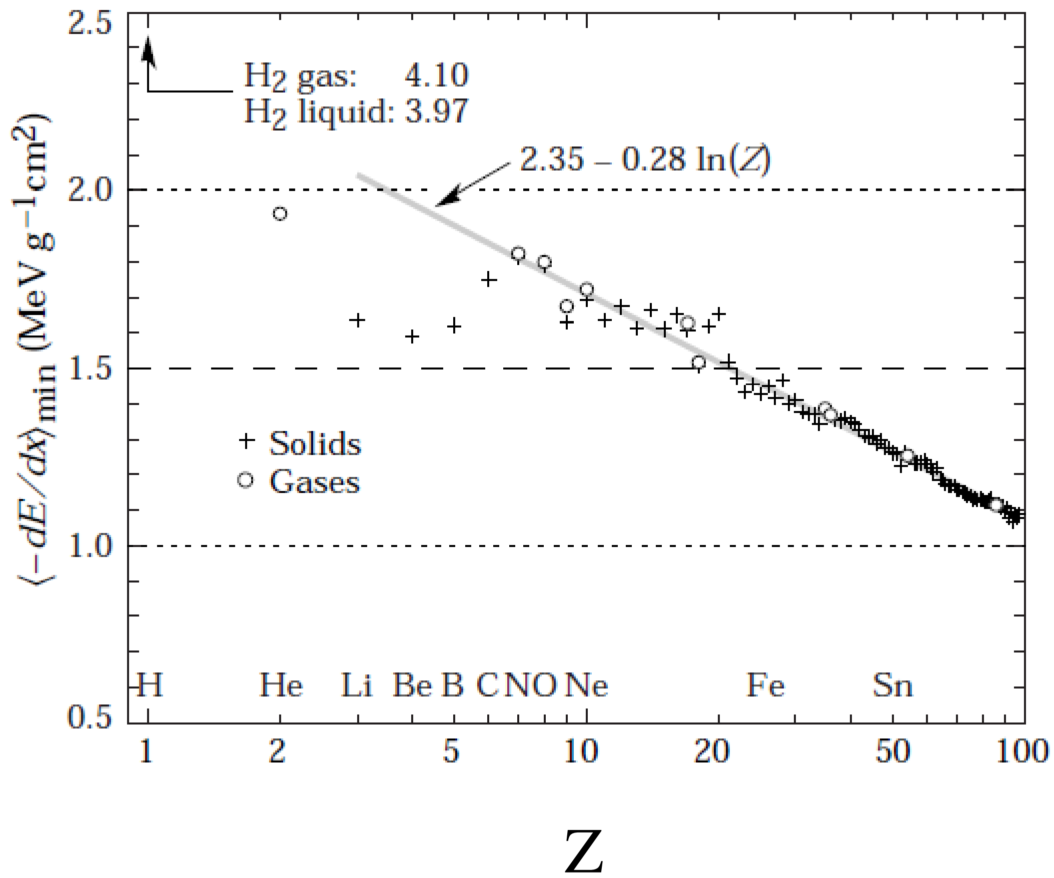
N. Bohr, Penetration of atomic particles through matter, *Kgl. Danske Videnskab. Selskab Mat.-fys. Medd.* **XVII**, No. 8 (1948)

Stopping power for μ⁺ in copper



from RPP 2006

Stopping power for minimum ionizing particles in different elements



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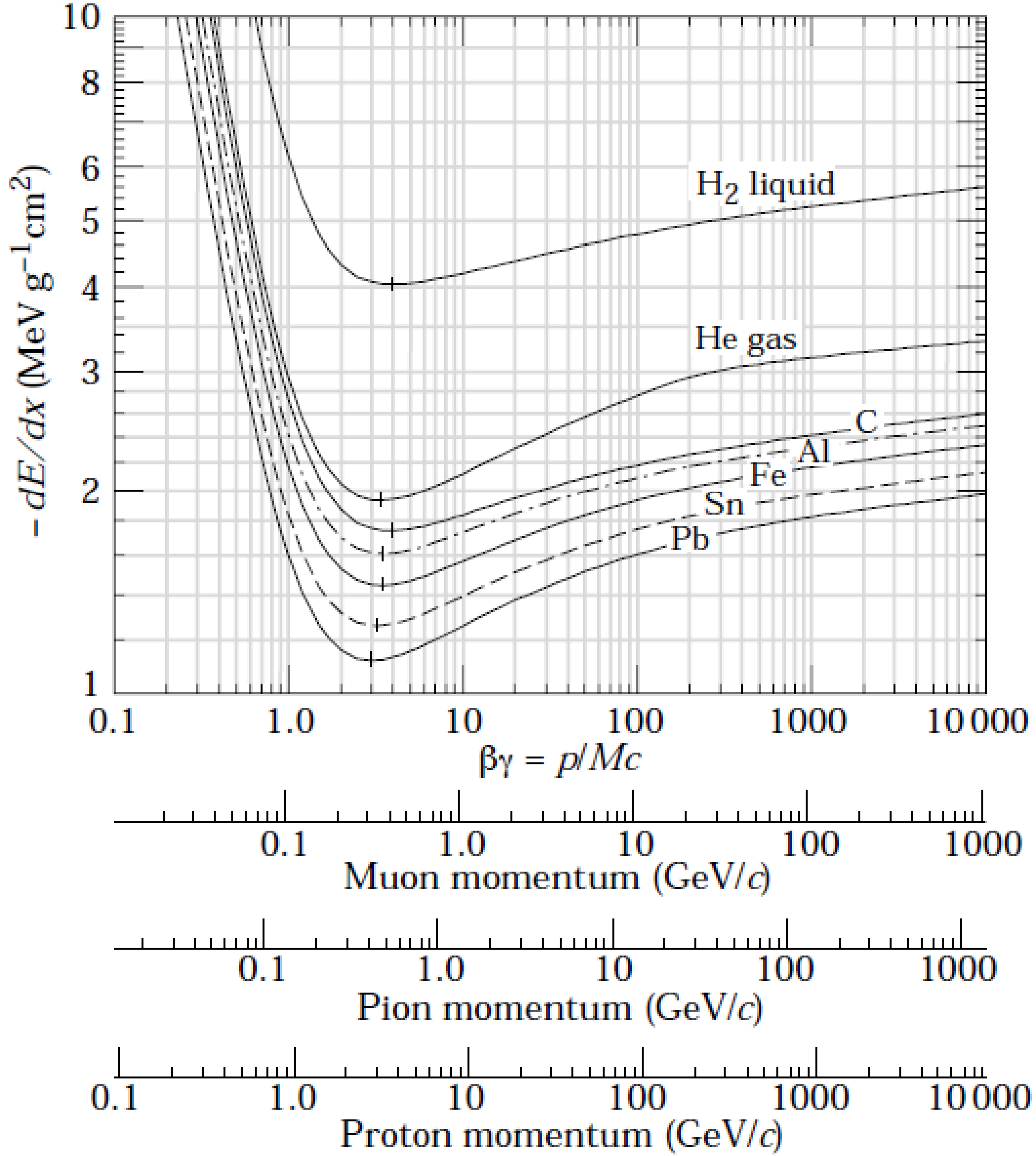
Stopping power for various particles in elements (no radiative losses)



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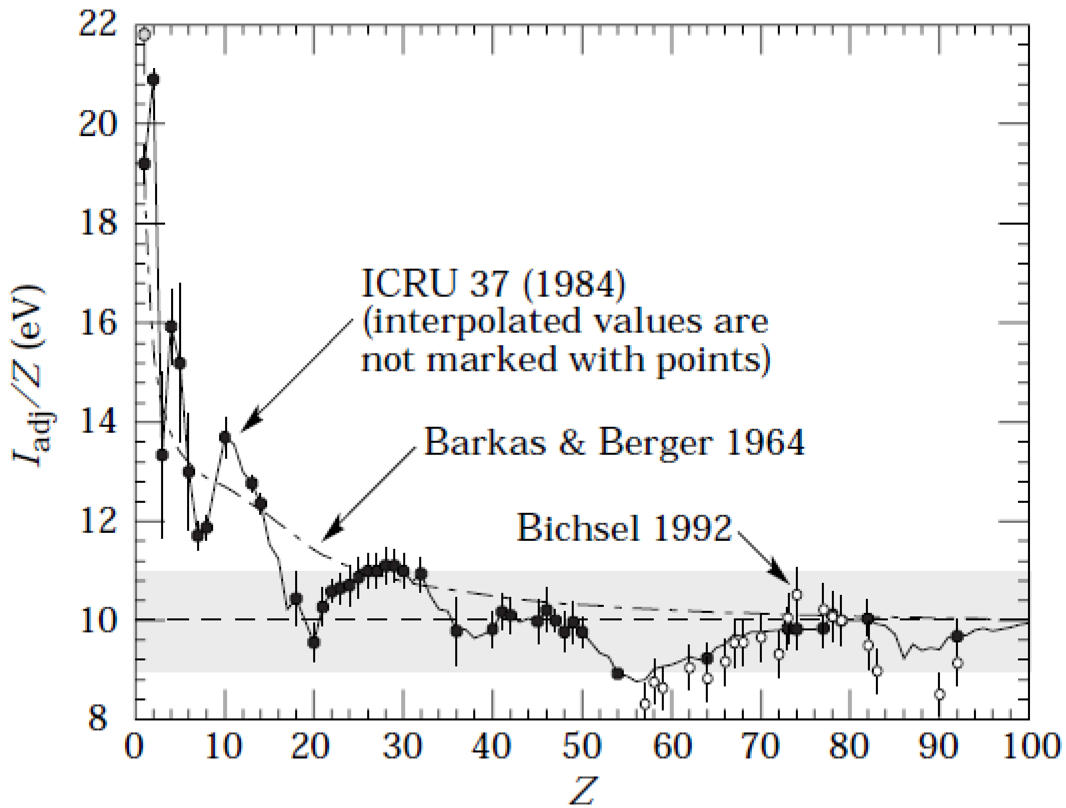
Mean ionization potential for various elements



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Applications:

1. Range of charged particle

2. Stopping time

   Doppler shift Attenuation Method (DSAM) for fast gamma transition lifetime measurements

3. ΔE-E telescope for identifying particle Z, A, E

1. Range

$$R = \int dx = \int dx/dE.\, dE = \int dE/S(E)$$

$$= \int dE/(KMZ^2)\,.\,E^{\alpha}$$

$$= [E^{1+\alpha}/(1+\alpha)]/(KMZ^2)$$

For particles such as protons to heavy ions $\alpha \sim 1.6 - 1.8$

$\Rightarrow$ $R \propto E^{1.7}$

$\Rightarrow$ Typically a 10 MeV proton stops in 709 μm Si (ΔR= 32.7 μm) while 120 MeV ^{12}C stops in 245 μm Si (ΔR= 9.9 μm)

Use: Choose detector thickness with margin for possible inadequacy of SRIM calculation and straggling

2. Stopping time

$$T_{stop} \sim R/\langle v_p \rangle = R/(\kappa v_p) \propto E^{1+\alpha} / (\kappa E^{1/2}) \propto E^{0.5+\alpha}$$

For uniform deceleration α=0.5, in reality closer to 0.6

For 10 MeV protons in Si, $T_{stop} \sim 26$ psec

Applied to DSAM for gamma ray measurement of nuclear lifetimes ~ 10^{-14} to 10^{-11} sec. Here excited nuclei recoil into backing and HPGe detector used to measure angle dependent Doppler profile.

3. ΔE-E telescope for identifying particle Z, A, E

$$\Delta E \propto MZ^2/E^{\alpha} \text{ where } \alpha \sim 0.7 \text{ to } 0.8$$

- Relatively easy to identify light particle isotopes, more difficult for heavier ones
- Easy to separate different atomic nos. (Z)
- For large range of ionic species, 3 element telescope used

2 estimates using Bethe-Bloch electronic stopping power

1. Energy loss for mip (cosmic muons) in prototype ICAL

   Fe plate thickness = 5 cm $\times$ 7.87 gm/cm^3

   $= 39.35$ gm/cm^2

   $\Rightarrow \Delta E \approx 63$ MeV for a muon exactly $\perp$ to plate and

   ≈ 756 MeV for 12 such plates

2. Energy loss in RPC gas gap : Thickness of freon gas at

   NTP ≈ 0.2 cm $\times$ 102 / (22.4 $\times$ 10^3) = 0.92 $\times$ 10^{-3} gm/cm^3

   $\Delta E \approx 0.92$ mg/cm^2 $\times$ 2 keV/(mg.cm^{-2}) $\approx$ 1850 eV

   If $\varepsilon_{\text{ion-e pair}} \sim 40$ eV, $N_{\text{ion-epair}} \sim 46$

Fluctuations in energy loss, range and angle

1. Energy loss fluctuations

$\sigma_E^2 = < E^2 > - < E >^2$

If $\Delta E_{mean} / W_{max} \geq 1$ Gaussian, thick absorber

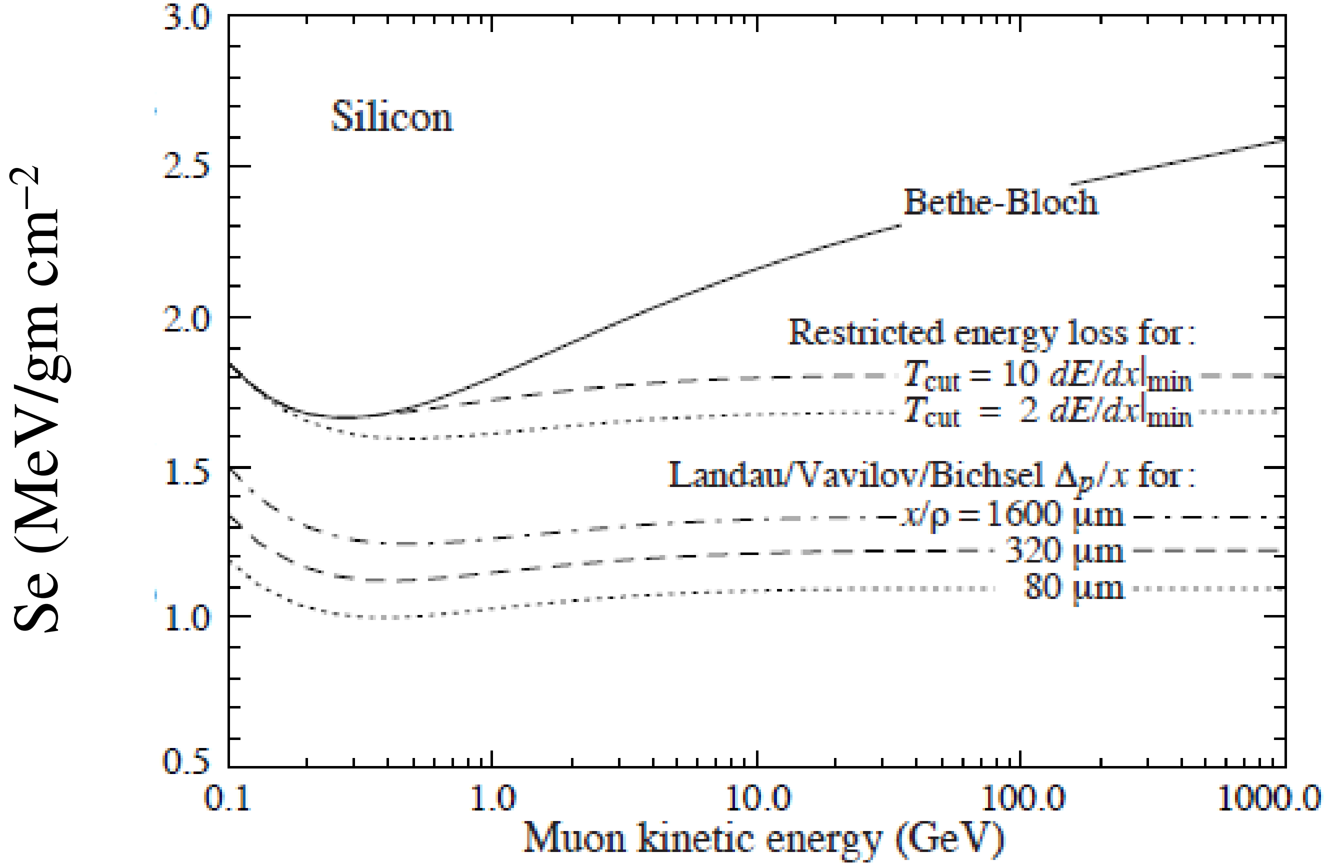
$\Delta E_{mean} / W_{max} < 0.01$ *Landau*, thin absorber

Intermediate $\Delta E_{mean} / W_{max}$ *Vavilov, Symon*

Bohr estimate (non-rel): $\sigma_E^2 = 0.1569 \, \rho \, Z/A \, . \, X$

& for relativistic particles $\sigma^2 = (1 - \beta^2/2)/(1 - \beta^2) \, . \, \sigma_E^2$

Bethe Bloch energy loss for muons & Landau most probable energy loss in Silicon



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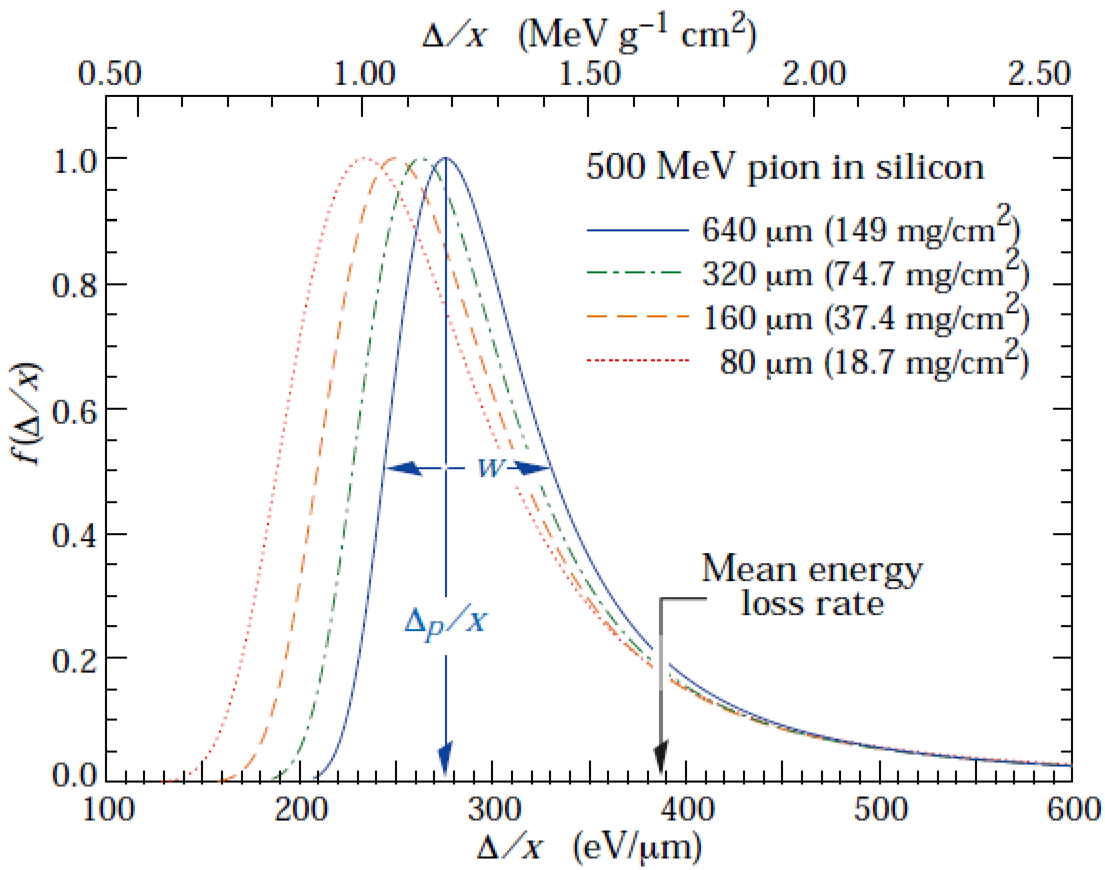
Energy straggling functions for 500 Mev pions in Si



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2. Range straggling

Stopping length of a heavy charged particle defined by range. This is an average quantity and the spread is known as range straggling. More for lighter ions as compared to heavy ions.

3. Angular straggling

$\sigma_\theta = 4\pi N_T (Z_P Z_T e^2/E_P)^2 \Delta x \,.\mathit{ln}\, (204\, Z_T^{-1/3})$

Another parametrisation (see RPP) is

$\sigma_\theta = 13.6 \text{ MeV}/(\beta cp).\, Z_P\sqrt{(x/X_0)}\, .\, [1 + 0.038 \ln(x/X_0)]$

where X_0 = radiation length, x =length traversed by charged particle

Extra slides

Kinds of radiation/particle detectors

Particle detectors are the eyes and ears of an experimental nuclear/particle physicist

What are the kinds of detectors?

Passive: plastic track detectors, photographic emulsions/films, mica…

Active (real time): Gas, scintillation, semiconductor, Cerenkov, tracking (using B-field)….