PHYSICS OF PARTICLE DETECTION

- We detect particles by exploiting some sort of interaction of the particles with the material in the detector

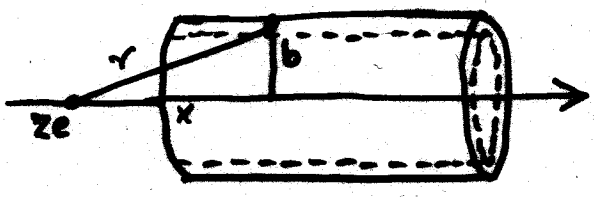
- Different physical processes are involved in the detection of charged and neutral particles.

- Charged particles passing through matter
  - lose energy
    → primarily due to interactions with atomic electrons (dominant loss)
  - scatter
    → primarily due to interactions/scattering off atomic nuclei

  Other Processes:
  - Production of em radiation
    → Čerenkov, Transition Radiation, Scintillation, bremsstrahlung (for electrons and high energy muons)

- Photons are detected/measured via photoelectric effect, Compton scattering or pair production
- Neutrons & neutrinos via strong & weak interactions respectively.

Energy Loss by Ionization



consider a heavy charged particle with charge ze and velocity v passing through some material.

The momentum transfered to an electron in the material, at a distance r and impact parameter b is,

$$\Delta p = \int_0^{\infty} F_\perp \, dt = \int_{-\infty}^{+\infty} \frac{ze \cdot e}{r^2} \cdot \frac{b}{r} \cdot \frac{dx}{v}$$

$$= \frac{ze^2}{v} \int_{-\infty}^{+\infty} \frac{b \cdot dx}{\left(\sqrt{b^2+x^2}\right)^3} = \frac{ze^2}{v \cdot b} \underbrace{\int_{-\infty}^{+\infty} \frac{d(x/b)}{\left(\sqrt{1+(x/b)^2}\right)^3}}_{=2}$$

$$= \frac{2ze^2}{b \cdot v} \quad -(1)$$

$\therefore$ The energy transfer is,

$$\Delta E = \frac{(\Delta p)^2}{2m} = \frac{\left(2ze^2/bv\right)^2}{2m} = \frac{2z^2e^4}{mb^2v^2} \quad -(2)$$

If we consider a cylindrical shell between b and b+db and in thickness dx, the energy transfered to electrons becomes,

$$-\Delta E(b) = \frac{2Z^2e^4}{mb^2v^2} \cdot n_e \cdot 2\pi b \cdot db \cdot dx$$

$$-\frac{dE}{dx} = \frac{4\pi n_e Z^2 e^4}{mv^2} \int_{b_{min}}^{b_{max}} \frac{db}{b} = \frac{4\pi Z^2 e^4}{mv^2} \ln \frac{b_{max}}{b_{min}} \quad -(3)$$

Use physical arguments to estimate b_{min}, b_{max}

The maximum transferable energy in a head-on collision is $(2\gamma m_e v)^2/2m_e = 2\gamma^2 mv^2$

$$2\gamma^2 mv^2 = \frac{2Z^2e^4}{m b_{min}^2 v^2} \quad \text{using (2)} \quad \therefore b_{min} = \frac{Ze^2}{\gamma mv^2}$$

The interaction must take place in a time short compared to the orbital period of the atomic electrons

$$t_{int} = \frac{b}{\gamma v} = \frac{1}{\nu} \quad \therefore b_{max} = \frac{\gamma v}{\nu}$$

$$\boxed{-\frac{dE}{dx} = \frac{4\pi n_e z^2 e^4}{m v^2} \ln \frac{\gamma^2 m v^3}{z e^2 \nu}}$$

Bohr's Classical Formula

A semiclassical approach: for b_{min}, b_{max}:

Assume min. impact parameter to be half the de Broglie wavelength of the electron

$$b_{min} = \frac{h}{2p} = \frac{h}{2\gamma m v}$$

As before,

$$b_{max} = \frac{\gamma v}{\nu} = \frac{h \cdot \gamma v}{h\nu} = \frac{h \cdot \gamma v}{I}$$

I = Ionization potential

$$\boxed{-\frac{dE}{dx} = \frac{4\pi n_e z^2 e^4}{m v^2} \ln \frac{2\gamma^2 m v^2}{I}}$$

Quantum Treatment:

A proper treatment of energy loss must take into account (1) that energy transfers to atomic electrons occur in discrete amounts and (2) the wave nature of particles. Such a treatment was done by Bethe & Bloch in early 1930's.

$$-\frac{dE}{dx} = n_e \int_0^\infty W \frac{d\sigma}{dW}(E, W)\, dW$$

$\frac{d\sigma}{dW}(E, W)$ = cross section for an incident particle with energy E to lose an amount of energy W in the collision with an electron. The transition probabilities for excitation or ionization of an electron are calculated using first order perturbation theory. the incident particle is treated as a plane wave.

$$-\frac{dE}{dx} = \frac{4\pi n_e Z^2 e^4}{m v^2}\left[\frac{1}{2}\ln \frac{2 m v^2 \gamma^2 \cdot E_{kin}^{max}}{I^2} - \beta^2\right]$$

Bethe - Bloch Formula

$$-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \cdot \frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2 m_e c^2 \gamma^2 \beta^2 E_{kin}^{max}}{I^2} - \beta^2 - \frac{\delta}{2} - \frac{2C}{Z}\right]$$

Correction needed at very low energies

N_A = Avogadro Number

r_e = Bohr Radius $= e^2/m_e c^2$

z = charge of the incoming particle

Z = Atomic number of the material

A = Mass number "

δ = Density Effect Parameter

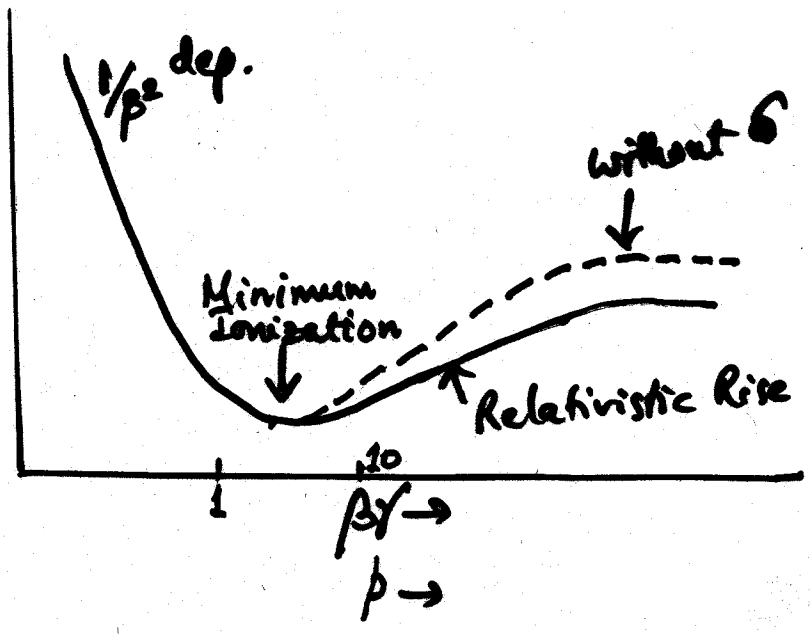
Also, used $n_e = Z \cdot \frac{N_A}{A} \cdot \rho$

and converted dE/dx to energy / gm · cm^{-2}

$$K = 4\pi N_A r_e^2 m_e c^2 = .307 \text{ MeV}/\text{g}\cdot\text{cm}^{-2}$$

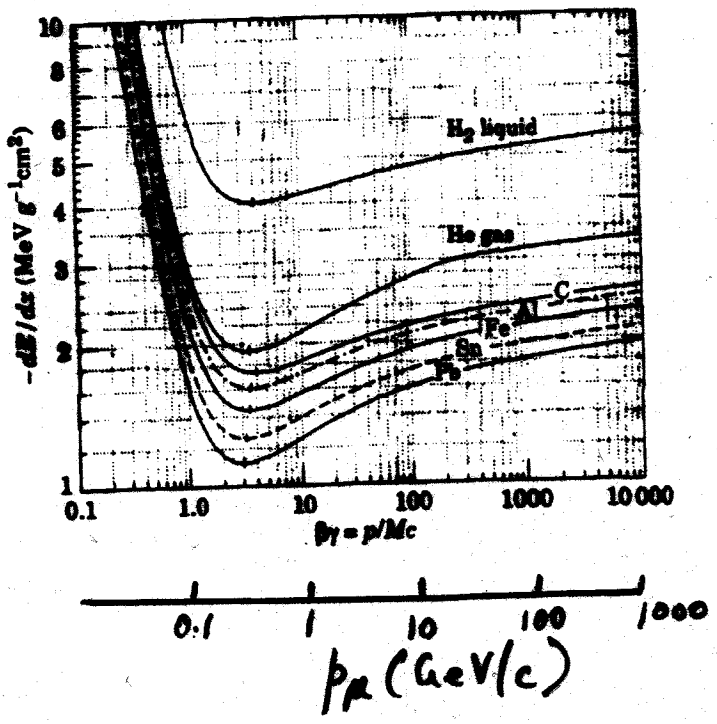
$$-\frac{dE}{dx} = \kappa \; z^2 \cdot \frac{Z}{A} \cdot \frac{1}{\beta^2} \cdot \left[\frac{1}{2} \ln \frac{2 m_e c^2 \gamma^2 \beta^2 E_{kin}^{max}}{I^2} - \beta^2 - \frac{\delta}{2} \right]$$

- $\frac{dE}{dx}$ first falls as $\frac{1}{\beta^2}$
- Reaches minimum at $\beta\gamma \simeq 4$ (MIP)
- Then rises due to $\ln \gamma^2$ term (contributions by more distant collisions)



- Relativistic rise cancelled by "density effect," screening of more distant atoms

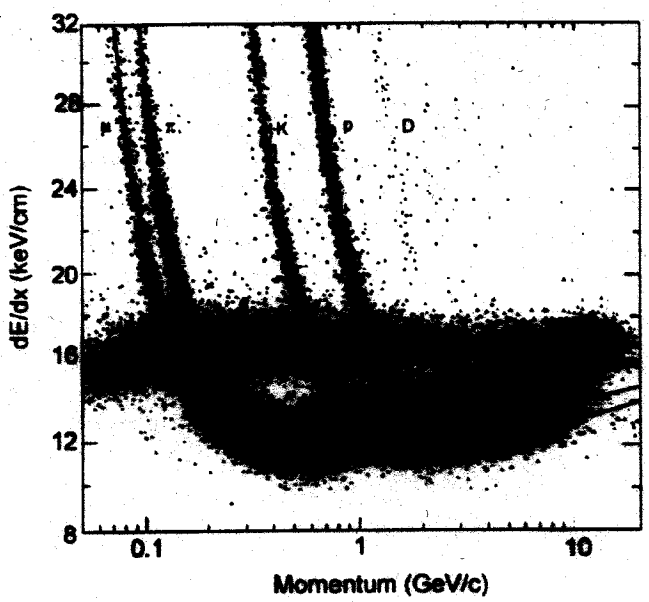
  $\rightarrow$ Fermi Plateau



$\frac{Z}{A}$ dependence

$$-\frac{dE}{dx}\Big|_{min}^{Fe} = 1.48\ \mathrm{MeV/g\,cm^{-2}}$$

$$= 11.65\ \mathrm{MeV/cm}$$



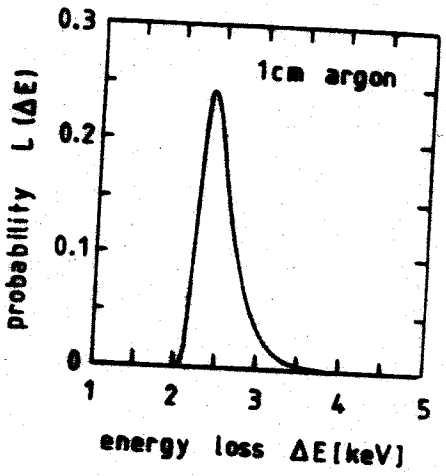
Measured dE/dx in the PEP4 TPC

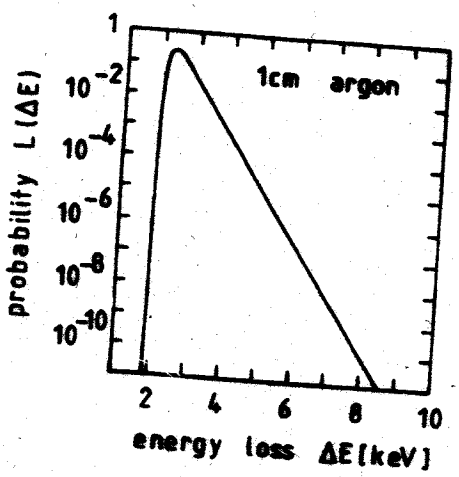
Mass dependence of dE/dx

$\Rightarrow$ Particle ID

$$\frac{dE}{dx} \propto \frac{1}{\beta^2} \propto \frac{M^2}{p^2}$$

The Bethe-Bloch formula gives us the mean/average energy loss. In thin absorbers, strong fluctuations around the average energy loss exist.





For depth L

$$\langle \Delta E \rangle = \left\langle \frac{dE}{dx} \right\rangle L$$

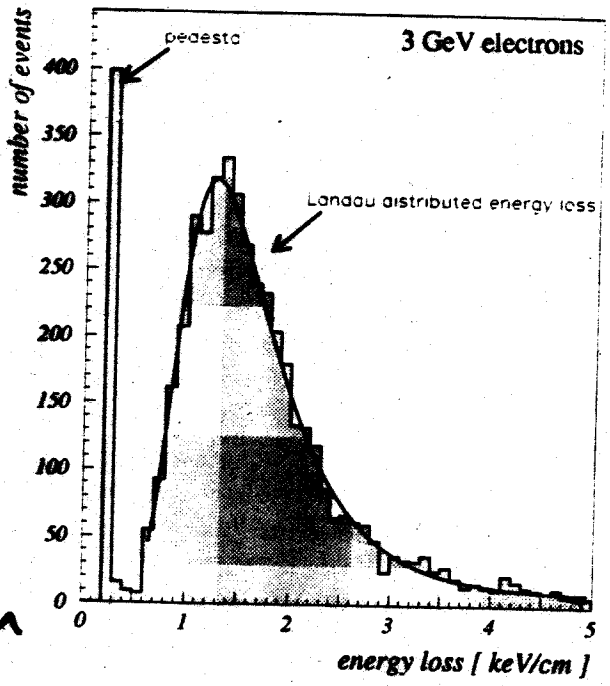
↑ Most probable energy loss

$$P(\lambda) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}(\lambda + e^{-\lambda})}$$

(Landau distribution)

$$\lambda = \frac{\Delta E - \langle \Delta E \rangle}{\langle \Delta E \rangle}$$

deviation from the m. p. energy loss

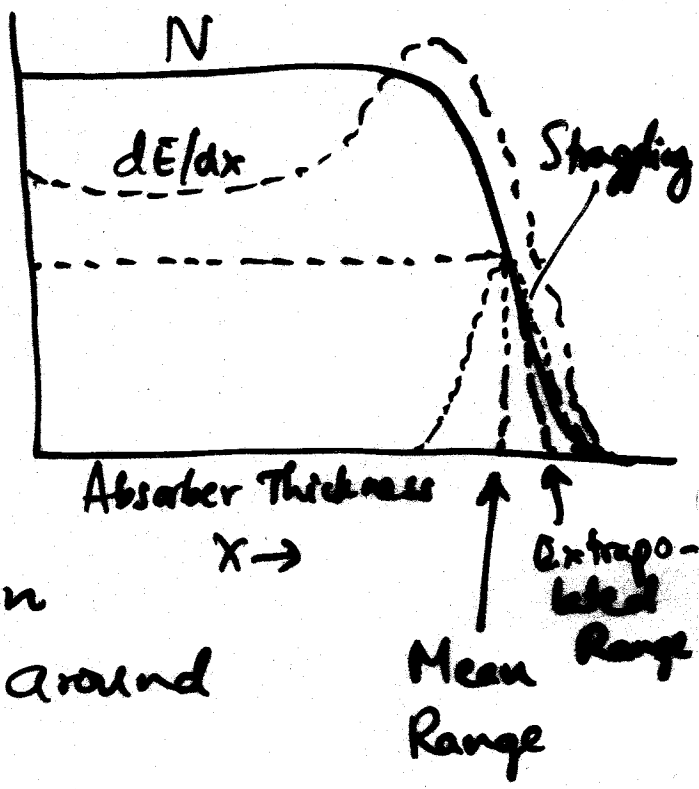


For thick absorbers, the energy loss distribution → Gaussian

Range & Straggling

Energy loss is statistical in nature.

Two identical particles with the same initial energy will have different number of collisions and hence different energy loss.



⇒ statistical distribution of Ranges centred around a "mean range".

→ Range – Straggling

$$R(E) = \int_E^{0} \frac{1}{-dE/dx} \cdot dE$$