Charged Particle Interactions

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Types of Particles

- Heavy charged particles
  - p, d, α, ions
- Electrons
Major Heavy Particle Interactions

- We observe:
  - loss of energy by the particle
  - deflection of the particle from initial direction

- primarily as a result of:
  - inelastic collisions with atomic electrons
  - elastic scattering from nuclei

- but other (less likely) processes are:
  - Cherenkov radiation
  - nuclear reactions
  - bremsstrahlung
Collision of Heavy Charged Particle with Atomic Electron
Bethe-Bloch formula

\[-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[ \ln \left( \frac{2 m_e \gamma^2 v^2 W_{max}}{I^2} \right) - 2\beta^2 \right]\]

In practice, however, two corrections are normally added: the density effect correction \( \delta \), and the shell correction \( C \), so that

\[-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[ \ln \left( \frac{2 m_e \gamma^2 v^2 W_{max}}{I^2} \right) - 2\beta^2 - \delta - 2 \frac{C}{Z} \right]\]
Bethe-Bloch formula definitions

\[ 2 \pi N_a r_e^2 m_e c^2 = 0.1535 \text{ MeVcm}^2/\text{g} \]

- \( r_e \): classical electron radius = \( 2.817 \times 10^{-13} \text{ cm} \)
- \( m_e \): electron mass
- \( N_a \): Avogadro's number = \( 6.022 \times 10^{23} \text{ mol}^{-1} \)
- \( I \): mean excitation potential
- \( Z \): atomic number of absorbing material
- \( A \): atomic weight of absorbing material
- \( \rho \): density of absorbing material
- \( z \): charge of incident particle in units of \( e \)
- \( \beta = \frac{v}{c} \): of the incident particle
- \( \gamma = \frac{1}{\sqrt{1 - \beta^2}} \)
- \( \delta \): density correction
- \( C \): shell correction
- \( W_{\text{max}} \): maximum energy transfer in a single collision.

The maximum energy transfer is that produced by a head-on or knock-on collision. For an incident particle of mass \( M \), kinematics gives

\[ W_{\text{max}} = \frac{2 m_e c^2 \eta^2}{1 + 2 s \sqrt{1 + \eta^2 + s^2}}, \]

where \( s = m_e / M \) and \( \eta = \beta \gamma \). Moreover, if \( M \gg m_e \), then

\[ W_{\text{max}} \approx 2 m_e c^2 \eta^2. \]
Bethe-Bloch with Corrections

\[
\frac{dE}{dx} \text{ [MeV cm}^{-2}\text{g}\text{m}]}
\]

- with corrections
- without corrections

Energy [MeV]
dE/dx for various heavy particles
Bragg Curve

\[ \frac{dE}{dx} \]

Penetration depth
Channeling In Crystals
Range Number-Distance Curve
Range Curves Heavy Particles
Computational Tools

- Generally, exact calculations are difficult due to multiple scatters, low energy effects, etc.
- Use SRIM 2000 as a computational tool for ion interactions in a variety of materials
- Program is on the lab computers in NW13-133
- Can be obtained on web
  - http://www.research.ibm.com/ionbeams/home.htm#SRIM
SRIM-2000 Input Data
Example of SRIM-2000 Output
5.79 MeV α in air
Cherenkov Radiation
Electron Interactions

- **Collisions**
  - Bethe-Bloch modified due to small electron mass

- **Bremsstrahlung**
  - Small electron mass makes this a major process above a few MeV (note that process is inverse to mass^4!)

\[ \sigma \propto r_e^2 = \left( \frac{e^2}{mc^2} \right)^2 \]
Radiation Loss vs. Collision Loss for Electrons
Range Number-distance for Electrons

Absorption of homogeneous $\beta$-rays in aluminium

Intensity

0  40  80

$g/cm^2$

0  0.2  0.4  0.6  0.8  1.0

421 keV  727 keV  1011 keV  1370 keV  1666 keV
Range Curves for Electrons

![Graph showing range curves for electrons in different materials (Polyethylene, Aluminum, Lead) as a function of energy. The x-axis represents energy in MeV, ranging from 0.1 to 100, and the y-axis represents range in g/cm², ranging from 10⁻² to 10².]
Absorption Curves for $\beta$ decay of $^{185}$W
Example of Multiple Scattering

\[
\begin{align*}
\theta & \quad \theta_x \\
\end{align*}
\]
Angular Distribution of Scatter

![Graph showing angular distribution of scatter]

- Fractional scattering per square degree
- Scattering angle [degrees]
- 18.66 mg/m²
- 37.28 mg/cm²

MIT Department of Nuclear Engineering
Electron Backscatter
Electron Backscatter Coefficients from Light Elements
Electron Backscatter from Heavy Elements
Radiation Loss vs. Collision Loss for Electrons
Practical Example: Electron LINAC

Rough rule for LINAC gives $R$ (Rad/min/mtr) as function of accelerator energy in MeV and current in $\mu$A. Energy spectrum is flat but photon spectrum shows increase at low energy:

$$R = 0.07i_{\text{avg}} E^{2.67}$$

$$\frac{dW}{dE} = k$$

$$\frac{dN}{dE} = \frac{dN}{dW} \frac{dW}{dE} = \frac{k}{E}$$

Thick target correction reduces low energy increase.
Bremsstrahlung With Thick Target