Energy Deposition

• Critical for experimentation. How do we
  - Detect
  - Identify
  - Determine properties of elementary particles?

• In practice, although we may be studying the **strong** or **weak** nuclear force, we detect elementary particles most directly through **electromagnetic** interactions.
Major Energy Deposit Mechanisms

- **Charged particles**
  - Ionization
  - Bremsstrahlung

- **Photons**
  - Photoelectric Effect
  - Compton Scattering
  - Pair Production
Cosmic Radiation and “Air Showers”

- Primary cosmic rays consist primarily of protons and heavier atomic nuclei (< 1% electrons, gammas...)
- The primary cosmic rays interact in the upper atmosphere to produce large “showers” of secondary particles.
- Secondaries (largely “muons”) reach Earth.
- How do we study these muons?
Stopping Power in Ionization Regime

\[ S = -\frac{dE}{dx} = n_{ion} \bar{I} \]

- Stopping power
- Energy loss per unit length
- Electron-ion pairs per unit length
- "Mean" ionization energy
Bethe-Bloch Equation

\[ S = \frac{4\pi Q e^2 n Z}{m_e \beta^2 c^2} \ln \left( \frac{2m_e c^2 \gamma^2 \beta^2}{\bar{I}} \right) - \beta^2 \]

- **Charge of particle**
- **Atomic charge of material**
- **Electron mass**

\( n = \text{number of atoms of material per unit volume} \)
Bethe-Bloch Equation

\[ S = \frac{4\pi Q e^2 n Z}{m_e \beta^2 c^2} \left[ \ln \left( \frac{2m_e c^2 \gamma^2 \beta^2}{I} \right) - \beta^2 \right] \]

Nonrelativistic case; e.g. nuclear alpha particles
Relativistic Behavior of Bethe-Bloch
The graph illustrates the stopping power of a muon on copper ($\mu^+$ on Cu) as a function of the Bethe range ($\beta\gamma$) and muon momentum. The graph shows different processes including nuclear losses, radiative losses, and radiative effects reaching 1%. The stopping power is measured in units of MeV cm$^2$/g. The graph also distinguishes between Bethe and radiative effects. 

Source: pdg.lbl.gov
Bremsstrahlung

- “Braking Radiation” (German)
- Classically; accelerated charge radiates
  - Electrons (light) radiate most
  - Heavier charges do too
- Quantum mechanically;
Radiation Length

\[ S_{\text{tot}} = S_{\text{ion}} + S_{\text{rad}} \]

\[ S_{\text{rad}} = -\left( \frac{dE}{dx} \right)_{\text{rad}} = \frac{4nZ^2\alpha^3(\hbar c)^2}{m^2c^4} E \ln \left( \frac{183}{Z^{1/3}} \right) \]

\[ \rightarrow \text{Since} \quad -\left( \frac{dE}{dx} \right)_{\text{rad}} = \text{constant} \times E \]

\[ = \frac{1}{L_R} E \]

\[ \text{We have...} \quad E = E_0 e^{-x/L_R} \]
# Radiation Lengths

<table>
<thead>
<tr>
<th>Element</th>
<th>Z</th>
<th>$L_R$ (cm)</th>
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<tbody>
<tr>
<td>H</td>
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<tr>
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<tr>
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<td>0.56</td>
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<tr>
<td>U</td>
<td>92</td>
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Photon Interactions

- Photoelectric Effect
- Compton Scattering
- Pair production

Energy increasing
Photoelectric Effect

- Dominates at energies few eV to few keV
- Knock atomic electrons out of orbit
- Evidence for photons
- Detector possibilities...
Photoelectric Effect

- Dominates at energies few eV to few keV
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Photomultiplier Tube

Figure 1

- Incoming Photon
- Photocathode
- Window
- Dynodes
- Anode
- Focusing Electrode
- Voltage Dropping Resistors
- Power Supply
- Output Meter
Compton Scattering

• Photon energy $\gg$ atomic binding energies
• Effectively scattering off of “free” electrons

$$\lambda_f - \lambda_i = \Delta \lambda = \frac{h}{m_0 c} (1 - \cos \theta)$$
Pair Production

- Possible once $E_\gamma > 2 \times m_e$