PHYS 3446 – Lecture #11

Wednesday, Mar. 2, 2005

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1. Energy Deposition in Media
   - Photon energy loss
   - Interaction of Neutrons
   - Interaction of Hadrons
2. Particle Detectors

Ionization Process

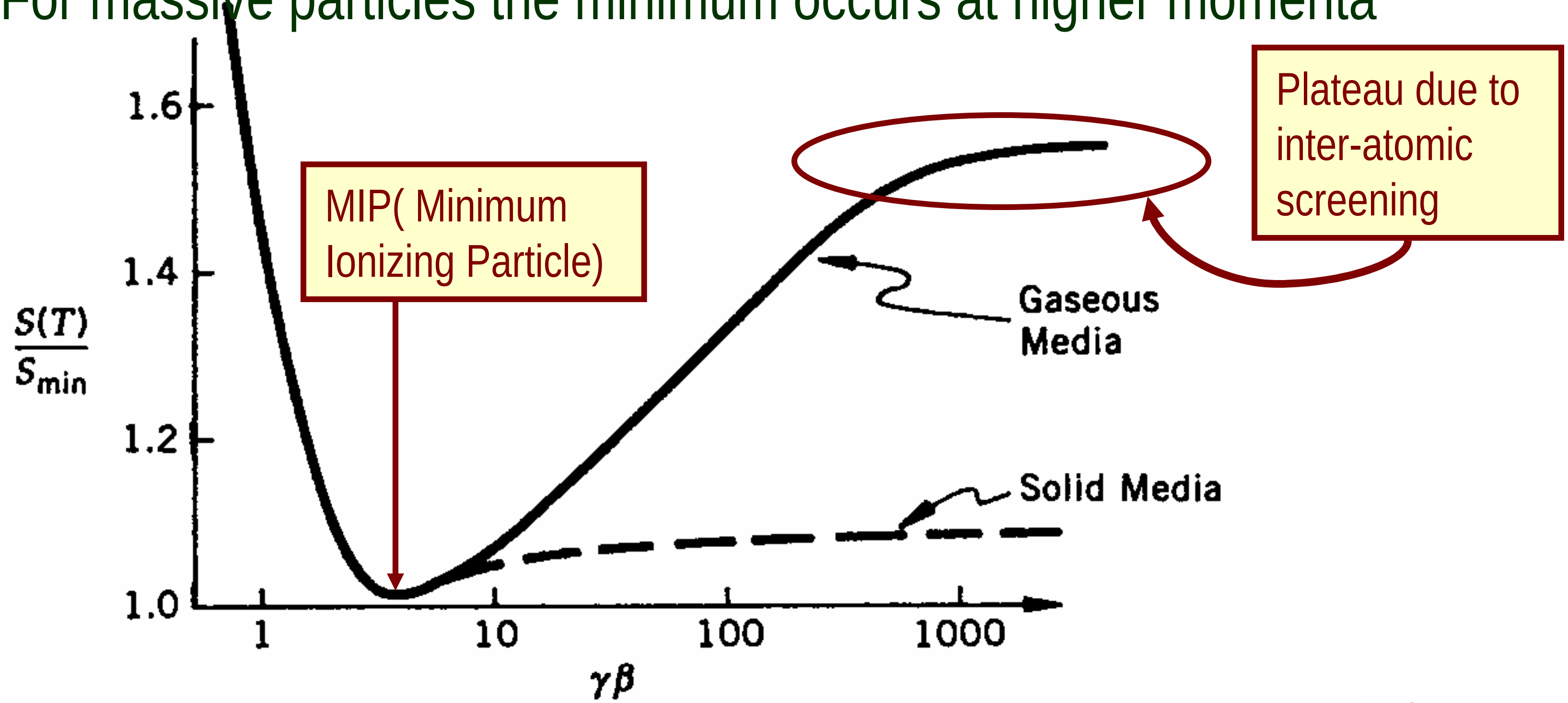
- For any given medium, the stopping power is a function of incident particle's energy and the electric charge
- Since ionization is an EM process, easily calculable
  - Bethe-Bloch formula

$$S(T) = -\frac{4\pi (ze)^2 e^2 nZ}{m\beta^2 c^2}\left[\ln\left(\frac{2mc^2\gamma^2\beta^2}{\bar{I}}\right) - \beta^2\right]$$

  - z: Incident particle atomic number
  - Z: medium atomic number
  - n: number of atoms in unit volume

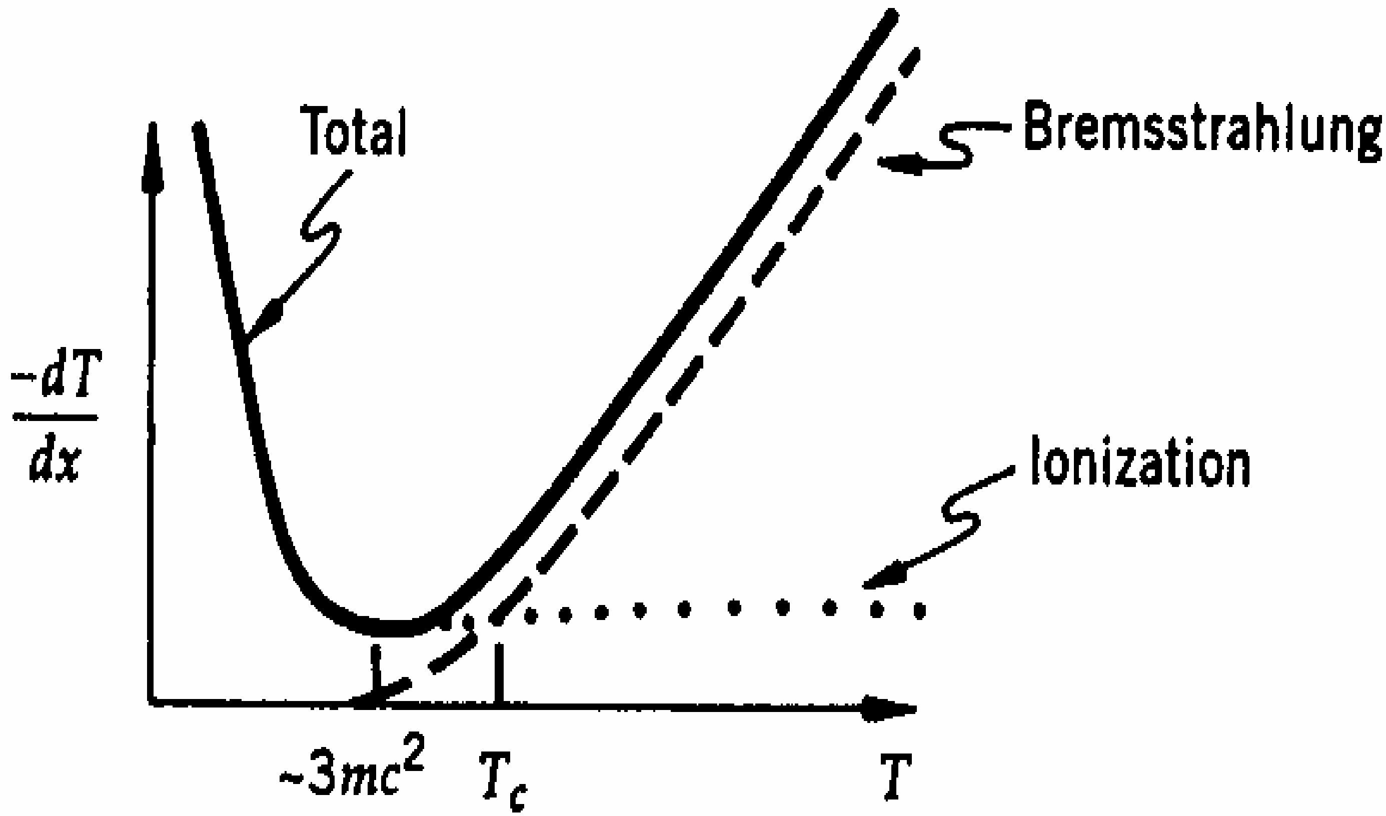
Properties of Ionization Process

- Stopping power decreases with increasing particle velocity independent of particle mass
  - Minimum occurs when $\gamma\beta$~3 (v>0.96c)
    - Particle is minimum ionizing when v~0.96c
    - For massive particles the minimum occurs at higher momenta



Total Electron Energy Loss

- Above the critical energy (T_c) the brem process dominates
$$\left(\frac{dT}{dx}\right)_{brem} = \left(\frac{dT}{dx}\right)_{ion} = -\frac{T_c}{X_0}$$



Photon Energy Loss

- Photons are electrically neutral
  - They do not feel Coulomb force
  - They cannot directly ionize atoms
- Photons are EM force carriers
  - Can interact with matters resulting in ionization
  - What are the possible processes?
    - Photo-electric effect
    - Compton scattering
    - Pair production

Light Attenuation

- Reduction of intensity in a medium
- Can be described by an effective absorption coefficient μ
  - μ reflects the total cross section for interaction
  - μ depends on energy or frequency of the incident light
- The intensity of light at any given point through the medium, x, is given as $I(x) = I_0 e^{-\mu x}$
- Half thickness, the thickness of material for photon's intensity to be half the initial intensity: $x_{1/2} = \frac{\ln 2}{\mu} = \frac{0.693}{\mu}$
- μ^{-1} is the mean free path for absorption

Photo-electric Effect

- Low energy photon is absorbed by a bound electron of an atom
  - The electron then subsequently emitted with T_e
  - The energy of electron T_e is $T_e = h\nu - I_B$

- I_B: Energy needed to free the atomic electron
- ν: Frequency of the incident photon

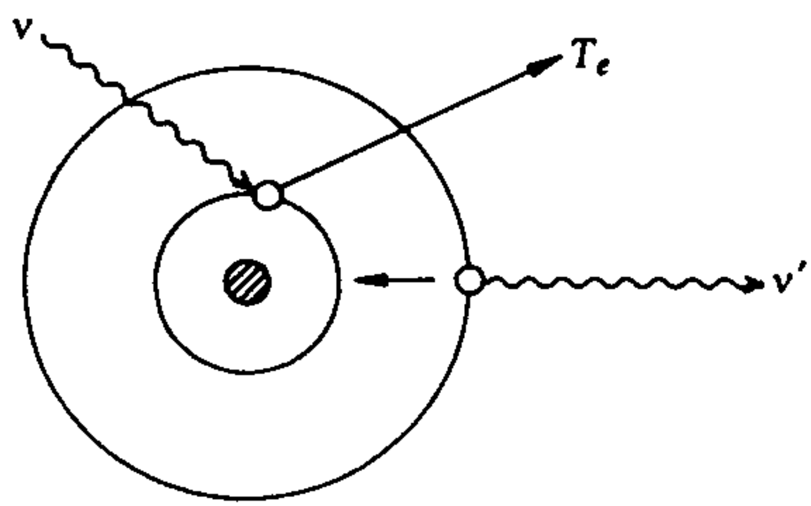


Photo-electric Effect

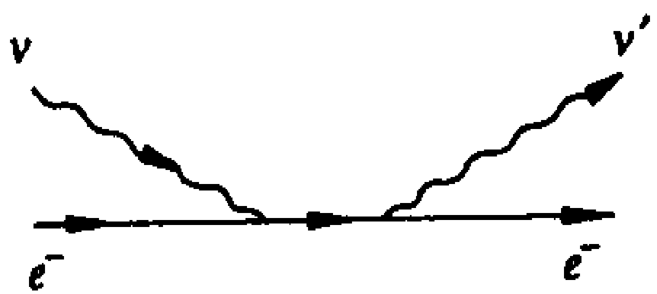
- The energy IB sets the threshold photon energies for this process to take place
- Photo-electric effect cross section is large in the range of X-ray energies (keV)
- The scale of cross section is

$$\sigma \approx \frac{Z^5}{(h\nu)^{7/2}} \quad \text{for} \quad E_\gamma < m_e c^2 \quad \text{and} \quad \sigma \approx \frac{Z^5}{h\nu} \quad \text{for} \quad E_\gamma > m_e c^2$$

- What do you conclude from these?
  – This process is particularly important for high Z medium
  – Not very significant above 1MeV photon energies
  – When an inner electron is emitted, photons from transition accompany the electron

Compton Scattering

- Equivalent to photo-electric effect on a free electron
  - Like a collision between a photon with energy $E=h\nu$ and momentum $p=E/c$ on a stationary electron
  - Electron absorbs a photon
    - Forms an electron like system with excited state and with an unphysical mass (virtual system)
    - Emits a photon with different frequency as it de-excites into a physical electron



Compton Scattering

- The kinematics of the scattering assumes free electron
- Thus the results will not work for low energy (<100keV) incident photons where the effect of atomic binding can be important
- The emitted photon frequency to scattering angle is

$$\nu' = \frac{\nu}{1 + \frac{h\nu}{m_e c^2}\left(1 - \cos\theta\right)}$$

  - For finite scattering angle, E of scattered photon is smaller than that of incident one
  - Some incident photon E is transferred to electron, having recoil energy dependent on the scattering angle
  - This was an evidence for particle property of light

Pair Production

- When photon has sufficient energy, it can be absorbed in matter and produce a pair of oppositely charged particles
  - Should not violate any conservation laws, including quantum numbers
  - Most common ones are conversion to an electron and position pair
- Massless photons cannot produce a pair of massive particles without violating energy-momentum conservation
  - In photon's rest frame, the initial state energy is 0.
  - While final state energy is non-zero.
- Thus the pair production can only occur in a medium
  - Why?
    - A recoiling nucleus can absorb any momentum required to assure energy-momentum conservation

Pair Production

- What is the minimum energy needed to produce an electron-positron pair?
  - Twice the rest mass energy of the electron

$$h\nu \approx 2m_e c^2 = 2\times 0.511MeV = 1.022MeV$$

- The pair production cross section is proportional to Z^2
  - Z: atomic number of the medium
  - Rises rapidly and dominates all energy-loss mechanisms for photon energies above 10MeV or so.
  - It saturates and can be characterized by a constant mean free path for conversion
    - A constant absorption coefficient ➔ Electron radiation length of medium

$$X_{pair} = \left(\mu_{pair}\right)^{-1} \approx \frac{9}{7} X_0$$

Pair Production

- What happens to the positron created in the conversion?
  - Positron is the anti-particle of the electron
  - Behaves exactly like electrons as they traverse through the matter
    - Deposit energy through ionization or bremsstrahlung
  - When it loses most of its kinetic energy, it captures an electron to form a hydrogen like atom, a positronium.
  - Positroniums are unstable and decay (annihilate) with a life time of 10^{-10} sec

$$e^{+}+e^{-}\rightarrow\gamma+\gamma$$

  - Why two photons?
    - To conserve the angular momentum
  - To conserve energy-momentum, the photon energies are exactly 0.511 MeV each
    - Good way to detect positronium

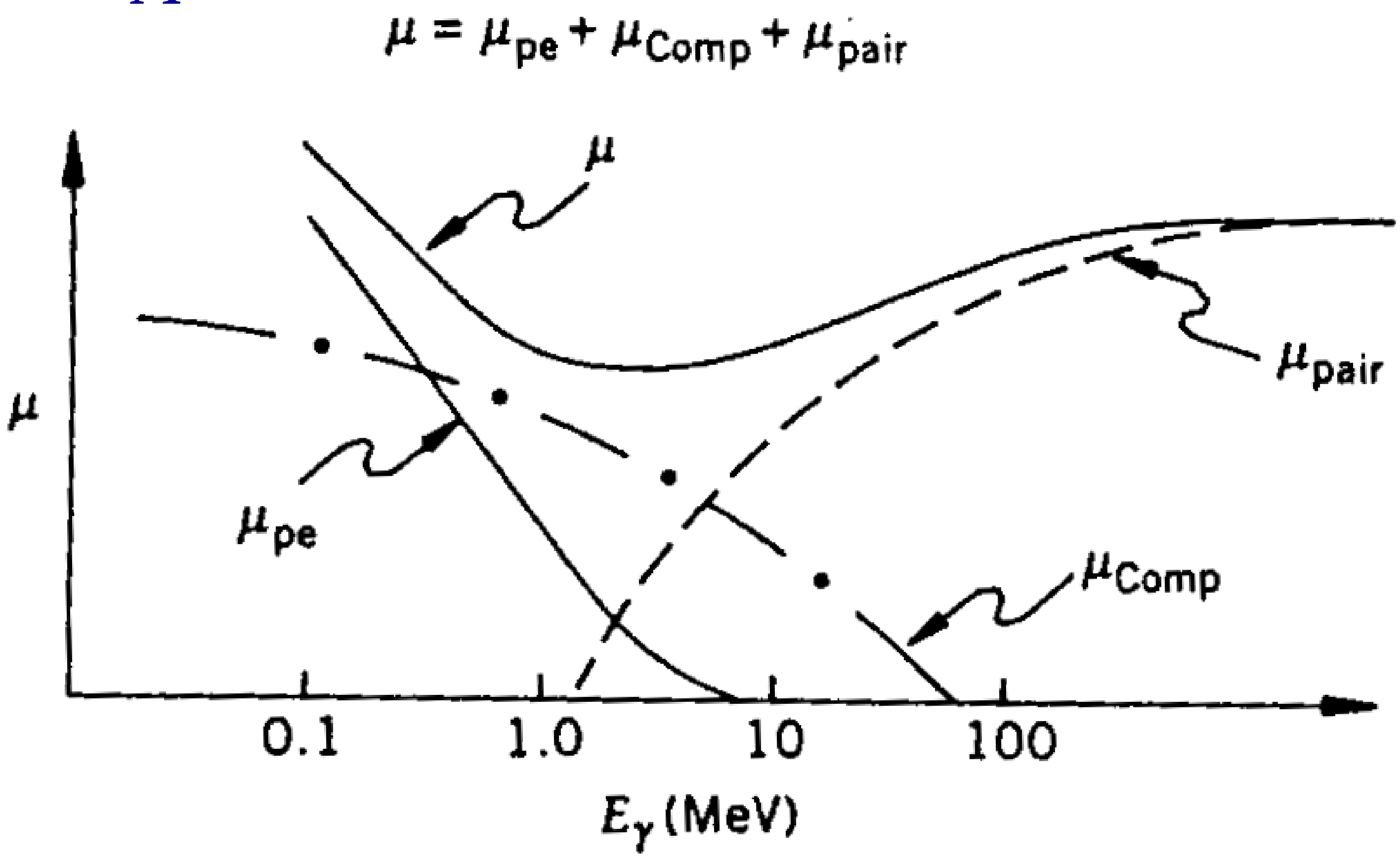
Photon Energy Loss Processes

- Total absorption coefficient of photons in a medium can be written as

$$\mu = \mu_{pe} + \mu_{Comp} + \mu_{pair}$$

- The absorption coefficient can be related to the cross section as

$$\mu = \rho \frac{A_0}{A} \sigma = n\sigma$$



We

Interaction of Neutrons

- What are the characteristics of neutrons?
  - Constituent of nuclei
  - Has the same nucleon number as protons
  - Has the same spin as protons
  - Electrically neutral → Do not interact through Coulomb force
  - Thus interact through strong nuclear force
- When low energy neutrons interact inelastically
  - Nucleus get excited and decay to ground levels through emission of photons or other particles
  - Such photons or other particles can be detected through other processes

Interaction of Neutrons

- In an elastic scattering of neutrons, it loses smaller amount of energy if the media's nucleus is heavy
  - Hydrogen rich paraffin is used to slow down neutrons
- When neutrons are produced in experiments, they can penetrate deep
  - Since there are no hydrogen nuclei available for kinetic energy absorption
  - The neutron shine or "albedo" at accelerators and reactors is often a major source of background
    - Can only be reduced with the use of appropriate moderators

Interaction of Hadrons at High Energies

- What are hadrons?
  - All particles interact through the strong nuclear force
  - Examples?
    - Neutrons, protons, pions, kaons, etc
- Protons are easy to get to and interact with other particles to produce mesons
  - At low (<2GeV) energies cross section between different particles differ dramatically
    - The collision cross sections of any two hadrons vary rapidly with energy
    - Nuclear effect is significant
  - Above 5GeV, the total cross section of hadron-hadron interaction changes slightly as a function of energy
    - Typical size of the cross section is 20 – 40 mb at 70 – 100 GeV
    - And increase logarithmically as a function of energy

Interaction of Hadrons at High Energies

- Hadronic collisions involve very small momentum transfers, small production angles and interaction distance of order 1fm
- Typical momentum transfer in hadronic collisions are of the order $q^2 \sim 0.1\ (GeV/c)^2$
- Mean number of particles produced in hadronic collisions grows logarithmically
  - ~3 at 5GeV
  - ~12 at 500GeV
- High energy hadrons interact with matter, they break apart nuclei, produce mesons and other hadrons
  - These secondaries interact through strong forces subsequently in the matter and deposit energy

Assignments

1. Derive Eq. 6.22
2. End of chapter problems
    1. 6.1, 6.2 and 6.8
3. Due for these assignments is Wednesday, Mar. 9.