PHYS 3446 – Lecture #14

Tuesday,April 7, 2012
Dr. ***Brandt***

- Energy Deposition in Media
  - Ionization Process
  - Photon Energy Loss
  - Range

Projects

1 UA1 Higgs (non) discovery/Carlo Rubbia Nick Stadler, John Havens, Paul T.

2 Top Discovery CDF/Dzero John Crouch, Mattthew Gortman, Peter Hammel

3 J/Ψ (Charm quark) Michael Davenport, Charles Knight, Richard Humphries

4 Top Quark at LHC: Kathleen Brackney, David Soward, Kevin Strehl

5 Charged Higgs1 search/discovery: Ashley Herbst, Anthony Rich

6 Charged Higgs2: Kelly Claunch, Robert Mathews, Charles Jay

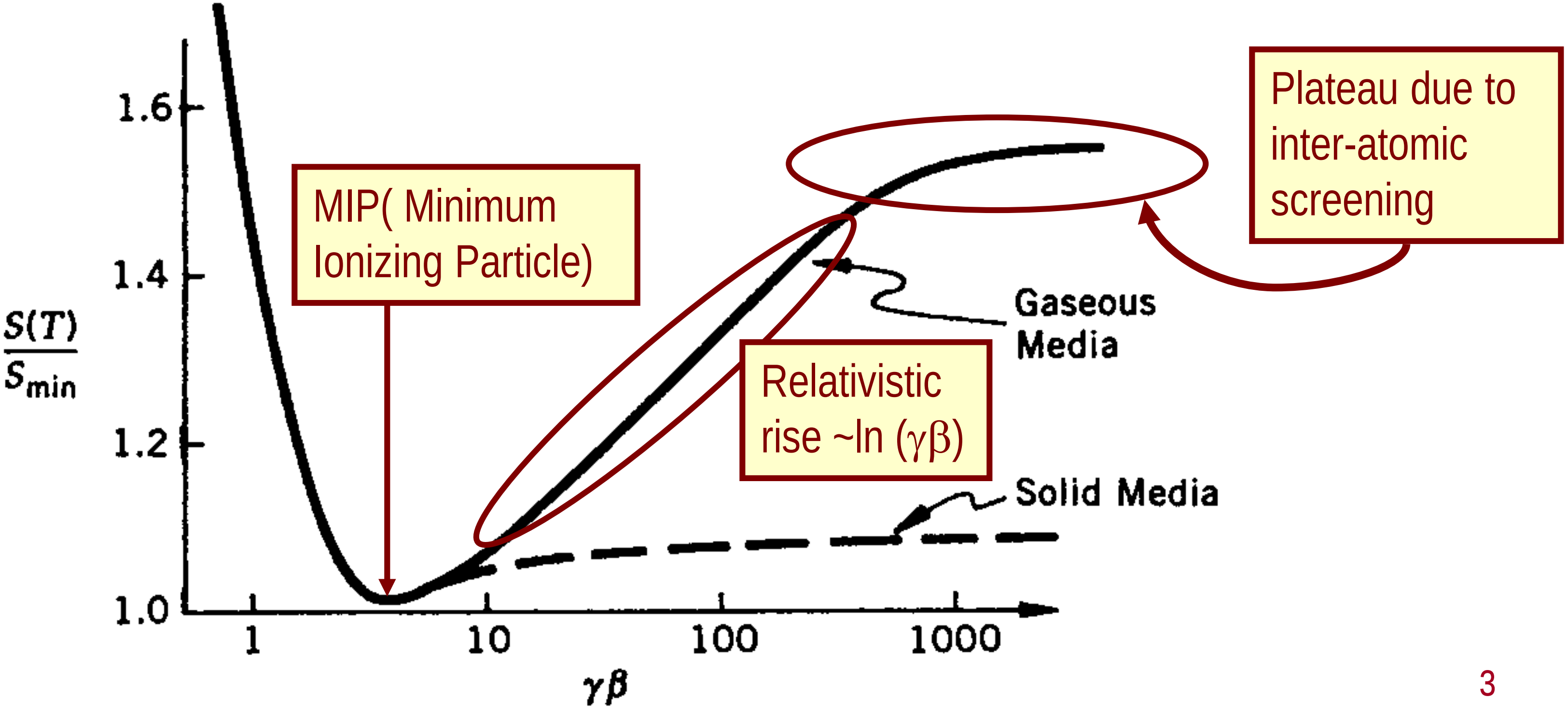
7 Higgs Discovery (ATLAS/CMS): Raul Dominguez, Peter Hamel, Kennedy

8 B quark Discovery: Garrett Leavitt, Bernard Nuar, Rajendra Paudel

1) Intro/Theory-what are you looking for and what is it's signature and background: how do you know if you find it
2) Detector-how is detector optimized for the task at hand, trigger/data collection
3) Analysis-operate on the data to accomplish the goals/Conclusion

Properties of Ionization Process

- Stopping power decreases with increasing particle velocity independent of incident particle mass
  - Minimum occurs when $\gamma\beta \sim 3$
    - Particle is minimum ionizing when v~0.96c
    - For massive particles the minimum occurs at higher momenta
  - This is followed by a $\ln(\gamma\beta)$ relativistic rise (see Beth-Bloch formula)
  - Energy loss plateaus at high $\gamma\beta$ due to long range inter-atomic screening effect which is ignored in Beth-Bloch



MIP(Minimum Ionizing Particle)

Relativistic rise ~ln (γβ)

Plateau due to inter-atomic screening

Ionization Process

- At very high energies
  - Relativistic rise becomes an energy independent constant rate
  - Cannot be used to distinguish particle-types purely using ionization
  - Except for gaseous media, the stopping power at high energies can be approximated by the value at $\gamma\beta\sim3$.
- At low energies, the stopping power expectation becomes unphysical
  - Ionization loss is very small when the velocity is very small
  - Detailed atomic structure becomes important

Ranges of Ionization Process

- Once the stopping power is known, we can compute the expected range of any particle in the medium
  - The distance the incident particle can travel in the medium before its kinetic energy runs out

$$R = \int_0^R dx = \int_T^0 \frac{dx}{dT} dT = \int_0^T \frac{dT}{S(T)}$$

- At low E, two particles with same KE but different mass can have very different ranges
  - This is why α and β radiation have quite different stopping requirements

Units of Energy Loss and Range

- What would be the sensible unit for energy loss?
  - MeV/cm
  - Equivalent thickness of g/cm^2: MeV/(g/cm^2)
- Range is expressed in
  - cm or g/cm^2 (units related through density)
- Minimum value of S(T) for z=1 at $\gamma\beta=3$ is

$$S(T)_{\min} \approx -\frac{4\pi e^4 A_0 (\rho Z/A)}{m\beta^2 c^2} \ln\left(\frac{2mc^2\gamma^2\beta^2}{\bar{I}}\right) \approx 5.2\times 10^{-7}(13.7-\ln Z)\rho Z/A \text{ erg/cm}$$

- Using <Z>=20 we can approximate

$$S(T)_{\min} \approx 3.5\frac{Z}{A}\ \mathrm{MeV}/\left(\mathrm{g/cm}^2\right)$$

Ex. 1+2

Multiple Scattering

- Phenomenological calculations can describe average behavior, but large fluctuations are observed on an event-by-event bases
  - This is due to the statistical nature of scattering process
- Statistical effect of angular deviation experienced in Rutherford scattering off atomic electrons in the medium
  - Consecutive collisions add up in a random fashion and provide net deflection of any incident particles from its original path
  - Called “Multiple Coulomb Scattering” ➔ Increases as a function of path length

$$\theta_{rms} \approx \frac{20MeV}{\beta pc} z \sqrt{\frac{L}{X_0}}$$

    - z:particle charge L: material thickness, X_0: radiation length of the medium (distance electron travels before T’=T/e)

Energy Loss Through Bremsstrahlung

- Energy loss of incident electrons
  - Bethe-Bloch formula works well (up to above 1 MeV for electrons)
  - But due to the small mass, electron's energy loss gets complicated
    - Relativistic corrections have large effect even down to a few keV level
    - Electron projectiles can transfer large fractions of energies to the atomic electrons they collide with
      - Produce δ-rays (ejected electrons) ➔ Which have the same properties as the incident electrons
  - Electrons are accelerated as a result of interaction with electric field by nucleus. What does this do?
  - Causes electrons to radiate or emit photons
    - Bremsstrahlung ➔ Braking radiation (as electron decelerates) an important mechanism of relativistic electron energy loss

Total Electron Energy Loss

- The electron energy loss can be written

$$\left(-\frac{dT}{dx}\right)_{tot} = \left(-\frac{dT}{dx}\right)_{ion} + \left(-\frac{dT}{dx}\right)_{brem}$$

- Relative magnitude between Bremsstrahlung and ionization is

$$\left(-\frac{dT}{dx}\right)_{brem} \Big/ \left(-\frac{dT}{dx}\right)_{ion} \approx \frac{TZ}{1200 m_e c^2}$$

  - Z: Atomic number of the medium, m_e: rest mass of the electron, T: Kinetic energy of the electron in MeV

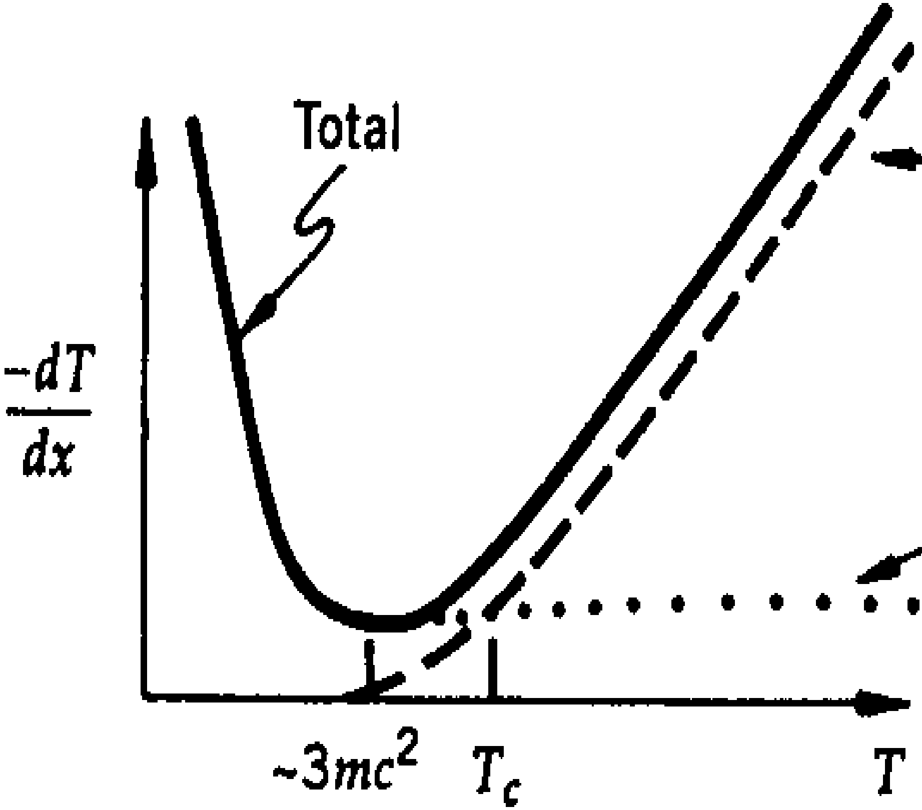
- At high energies, ionization loss is constant
  - Radiation dominates the energy loss
  - The energy loss is directly proportional to incident energy
  - $T=T_0\, e^{-x/X_0}$ (electrons radiate most of energy within a few radiation lengths)

Total Electron Energy Loss

- Above the critical energy (T_c) the brem process dominates

$$\left(\frac{dT}{dx}\right)_{brem} = \left(\frac{dT}{dx}\right)_{ion} = -\frac{T_c}{X_0}$$

$$X_0 \approx 170\frac{A}{Z^2}(g/cm^2)$$



radiation length=distance electron travels before its energy drops to T/e

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 matter resulting in ionization
  - What are the possible processes?
    - Photo-electric effect
    - Compton scattering
    - Pair production

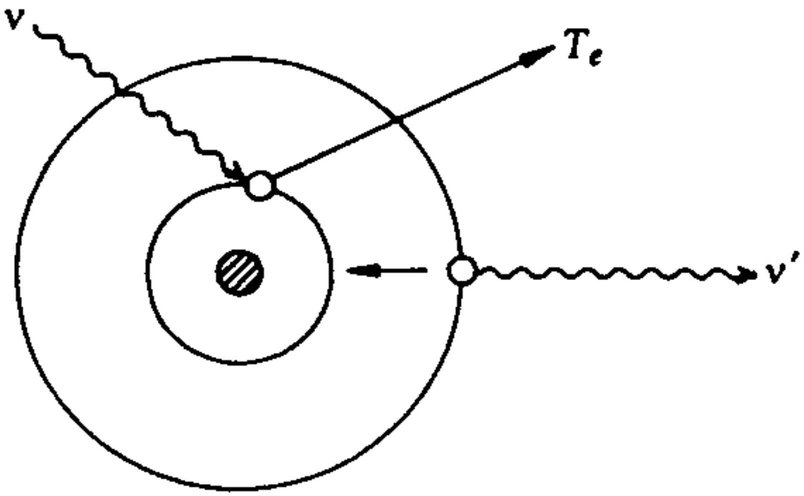
Light Attenuation

- 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 such that a photon's intensity is reduced by half: $x_{1/2} = \frac{\ln 2}{\mu} = \frac{0.693}{\mu}$
- μ^{-1} is the mean free path for absorption

Photoelectric Effect

- Low energy photon is absorbed by a bound electron in 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 given atomic electron
- ν: Frequency of the incident photon



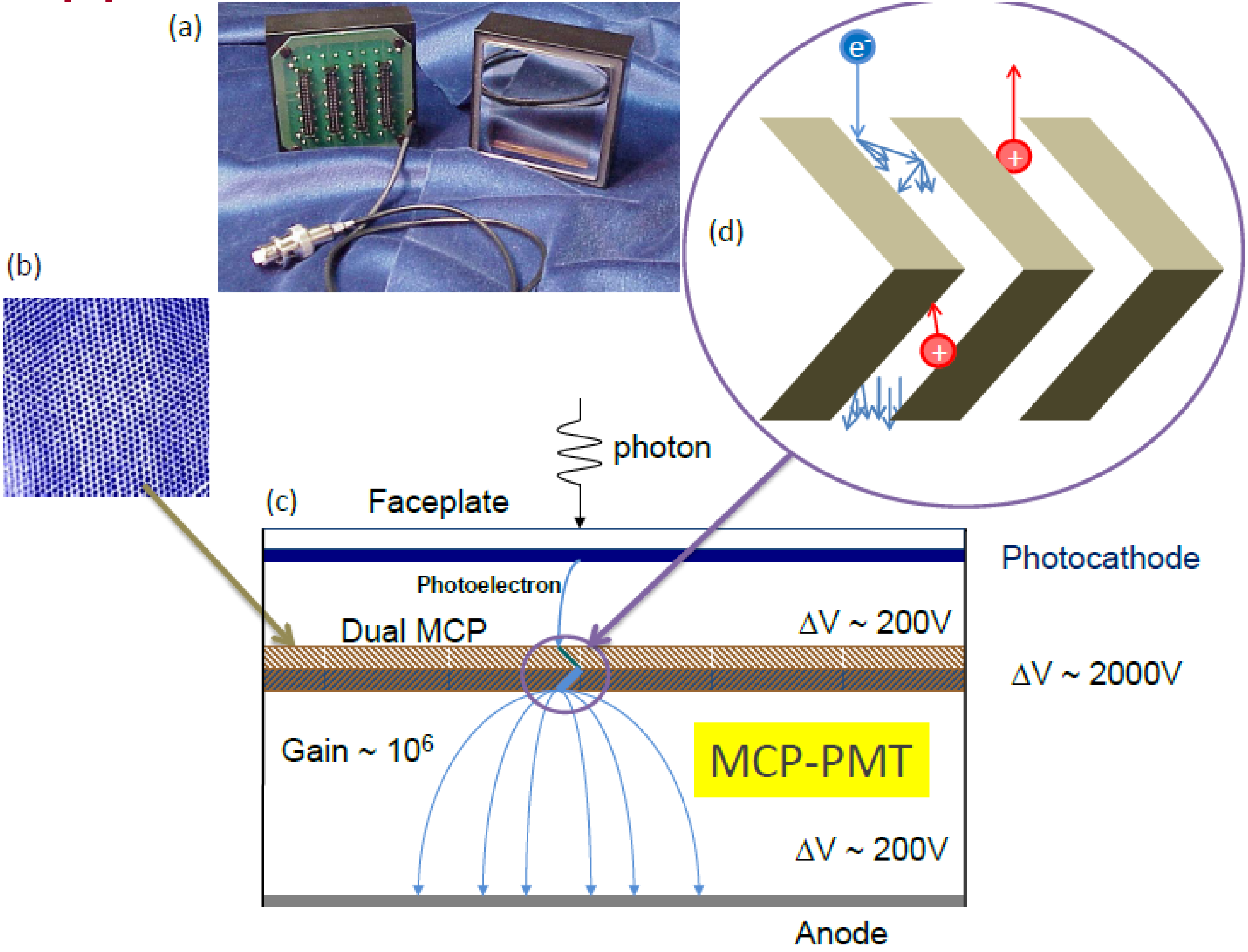
Photoelectric Effect

- The energy $I_{\mathcal{B}}$ 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

Application of Photoelectric Effect



Pair Production

- When a 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 is an electron and positron 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 pair production can only occur in a medium
    - 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

$$h\nu \approx 2m_e c^2 = 2\times 0.511MeV = 1.02MeV$$

- 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

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