Particle Interactions in Detectors

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Outline

- Introduction
- Energy Loss of *Heavy* Particles
- Energy Loss of Electrons and Positrons
- Interactions of Photons
- Scattering
- Cherenkov Radiation
- Interaction of Neutrons

Sources of Information

Quite a large number of books on elementary particle physics contain a description of the fundamental interactions of particles with matter.

I quite like these two general texts:
- Leo W R *Techniques for Nuclear and Particle Physics Experiments*, Springer-Verlag
- Ferbel T *Experimental Techniques in High Energy Physics*, Addison-Wesley

There are specialised ones for individual detector systems which often go into even more detail (probably more than you need or want!). However …

The Best Source?

26. PASSAGE OF PARTICLES THROUGH MATTER

Revised April 2002 by H. Bichsel (University of Washington), D.E. Groom (LBNL), and S.R. Klein (LBNL).

Chapter 26 of the Particle Data Group tables has everything! It is available (along with all the other chapters of course) at http://pdg.lbl.gov/

Introduction

- My aims are simple!
  - To give you an understanding of particle-matter interactions
  - To draw out the basic effects
  - To give you an "order of magnitude" feel for processes
  - To provide a background to my lectures on detectors.

Cross-section

- Measures the probability of an interaction
- Assume that on average N_s particles are scattered per unit time from a beam (of flux F) into an element of solid angle $d\Omega$

$$\frac{d\sigma}{d\Omega}(E,\Omega)=\frac{dN_S}{Fd\Omega}$$

For a thin target of area A (less than the beam area), the total number scattered into all angles is

$$N_{tot}=FAN\delta x\sigma$$

Heavy Charged Particles

- Protons, alphas, pions, muons …
  - Loss of energy
  - Change of trajectory
- Main processes
  - Inelastic atomic collisions ($\sigma \cong 10^{-16}$ cm^{-2})
  - Elastic scattering from nuclei
- Other processes
  - Cherenkov, nuclear, bremsstrahlung

Stopping Power (or *dE/dx)*

Classical calculation of Bohr (insight) then more complete QM treatment of Bethe, Bloch et al.

Bohr's assumptions:
•A particle of charge *ze* interacts with a free electron at rest
•No deviation of particle trajectory (e.g. really is massive)
•Impulse assumption (short time period)

$$I = \int F dt = e \int E_{perp} \frac{dt}{dx} dx = e \int E_{perp} \frac{dx}{v}$$

Stopping Power (or *dE/dx)*

Using Gauss' Law to calculate the integral

$$\int E_{perp} 2\pi b dx = 4\pi z e$$

where b is the impact parameter

The energy *gained* by the electron is

$$\Delta E(b) = \frac{I^2}{2m_e} = \frac{2z^2e^4}{m_e v^2 b^2}$$

Kinetic Energy dependence

Stopping Power (or *dE/dx)*

To calculate the total energy loss integrate over some range of impact parameters that *do not* violate the initial assumptions. One can get a reasonably useful formula (and one that is more or less relativistically correct by this procedure) however it doesn't work well for particles lighter than the alpha.

The proper solution is due to Bethe et al, and the energy transfer is parameterised in terms of momentum transfer rather than impact parameter. There is a detailed review of all the many corrections and refinements to the original formula of Bethe & Bloch available at:
http://www.srim.org/SRIM/SRIMPICS/THEORYCOMPONENTS.htm

"Bethe-Bloch" Formula

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

where the correction terms are :

δ the density effect correction and

$2\frac{C}{Z}$ due the shell correction C

Maximum energy transfer in a single collision

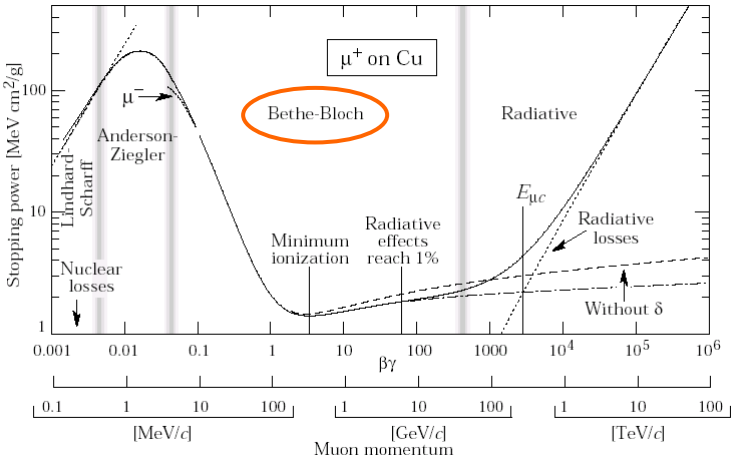
Mean excitation potential

"Bethe-Bloch" Formula

Note

- the initial fall as $1/\beta^2$
- the strong dependence on particle charge *z*
- the logarithmic *rise* for highly relativistic particles
- A *minimum* around $\beta = 0.96$ which is almost the same in magnitude for all particles with the same charge

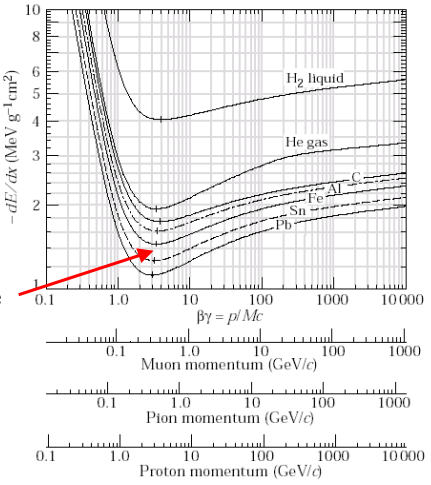
“Bethe-Bloch” Formula



From PDG tables, see http://pdg.lbl.gov/2002/passagerpp.pdf

“Bethe-Bloch” Formula

Note lack of dependence of the position of the minimum on the target



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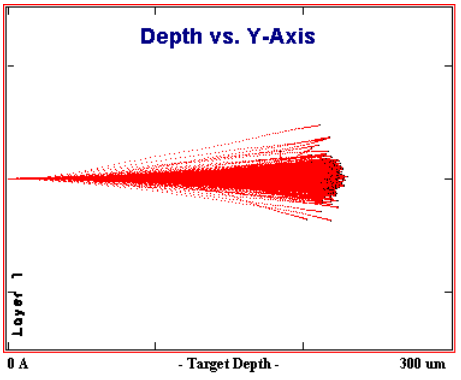
"Bethe-Bloch" Formula

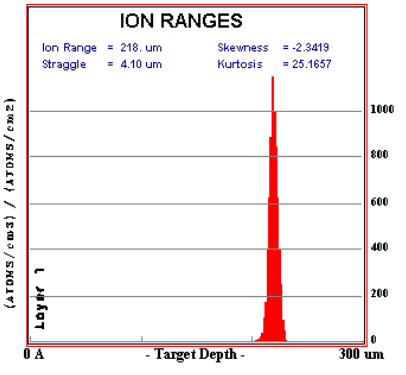
Re-writing the formula in terms of "mass thickness" (ρt) we find that :

$$-\frac{dE}{\rho dx} = z^2 \frac{Z}{A} f(\beta, I)$$

Z/A doesn't vary much, and the dependence on *I* comes in only logarithmically therefore the density normalised energy loss is almost independent of the material.

Particle Range

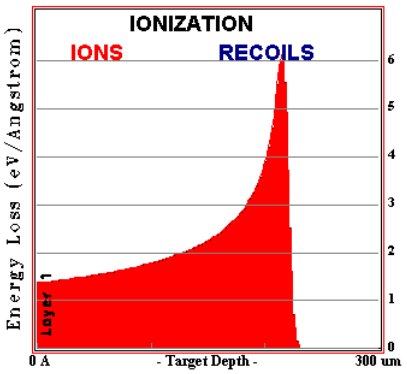




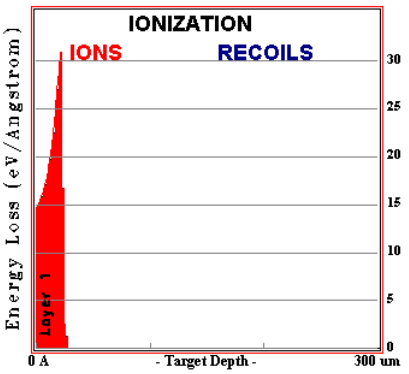
5 MeV proton into solid silicon

Monte Carlo simulation using SRIM code

Bragg Curve



5 MeV proton into solid silicon

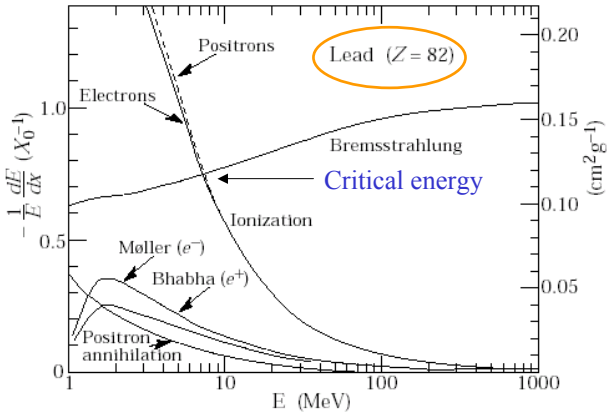


5 MeV alpha into solid silicon

Energy Loss of Electrons

- Electrons (and positrons) suffer collisional losses in passing through matter
- An additional *important* loss mechanism is EM radiation arising from scattering in the field of a nucleus (*bremsstrahlung*)
- For particle energies higher than a few tens of MeV bremsstrahlung losses DOMINATE.

Energy Loss of Electrons



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Energy Loss by Electrons

- The *critical energy* is the energy at which radiative and ionisation/collisional losses are equal
- It depends strongly on the absorbing material
- For Pb it is 9.5 MeV, for Al it is 51 MeV and for polystyrene it is 109 MeV
- Approximately you can use (for solids):

$$E_c \cong \frac{610\,\mathrm{MeV}}{Z + 1.24}$$

Radiation Length

- The *radiation length* (X_0) is defined as the distance over which the electron energy is reduced by a factor of $1/e$ due to radiation losses only.
- Radiation loss is more or less independent of material when thickness is expressed in X_0
- Extremely useful concept for design of calorimeters

Energy Loss for Photons

- Dramatically different processes for photons than for charged particles
  - Photoelectric effect
  - Pair production
  - Compton Scattering (+Thomson +Rayleigh)
  - Less important is
    - Nuclear dissociation

Energy Loss for Photons

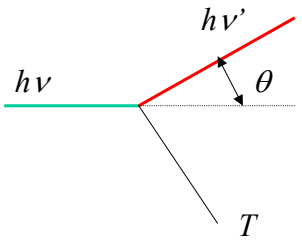
- Photoelectric effect
  - Absorption of a photon by an atomic electron followed by the subsequent ejection of an electron from the atom.
  - Nucleus absorbs the recoil momentum
  - For photon energies above the K-shell the absorption cross section varies approximately as Z^5
  - *Implies that high Z materials make good gamma ray detectors* e.g. NaI, BGO, CsI (all scintillating crystals).

Energy Loss for Photons

- Compton Scattering
  - Scattering of photons by *free* electrons
  - Outgoing photon has lower energy than incoming photon.

$$T = h\nu - h\nu' = h\nu \frac{\gamma(1-\cos(\theta))}{1+\gamma(1-\cos(\theta))}$$

where $\gamma = \frac{h\nu}{m_e c^2}$

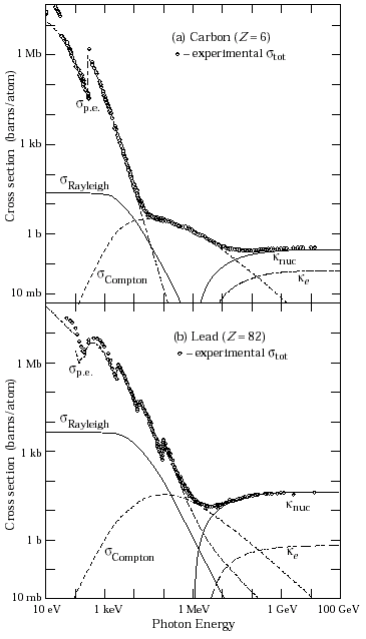


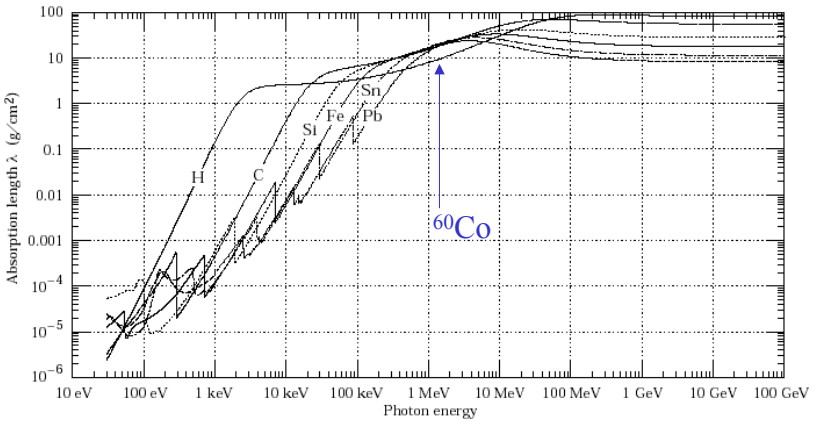
Energy Loss for Photons

- Pair production
  - Conversion of photon into electron+positron pair
  - Need a third body (momentum conservation), usually this is a nucleus.
  - Threshold energy is 1.022 MeV
  - Mean free path of a gamma ray for pair production is related to the radiation length for electrons:

$$\lambda_{pair} = \frac{9}{7} X_0$$

Photon absorption cross-sections in Carbon and Lead





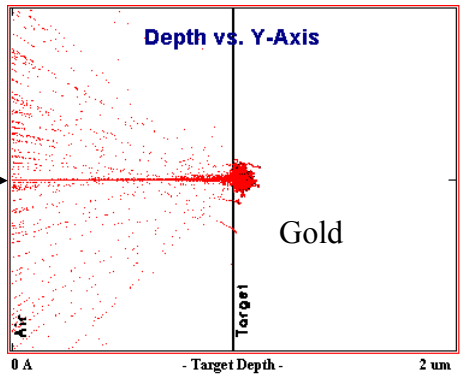
The photon mass attenuation length (or mean free path) for various elemental absorbers as a function of photon energy.
The intensity I remaining after traversal of thickness t (in mass/unit area) is given by $I = I_0 \exp(-t/\lambda)$.

Scattering

- As well as inelastic collisions with atomic electrons, particles also undergo *elastic* scattering from nuclei
- Classical formula due to Rutherford tells you that the cross-section varies approximately as θ^{-4}
  - Scattering produces mainly very small changes in particle trajectory
  - Cumulative effect of *multiple scattering* is however a net change.
  - For hadrons the strong and Coulomb interactions contribute to the effect.

Rutherford's Experiment

5 MeV alpha particles incident upon gold foil.



Scattering

- Distribution is roughly Gaussian but with longer tails (Rutherford scattering events with large single deviation)
- Defining $p, \beta,$ and z in the usual way then

If we define

$$\theta_0 = \theta^{\rm rms}_{\rm plane} = \frac{1}{\sqrt{2}}\,\theta^{\rm rms}_{\rm space}\ .$$

then it is sufficient for many applications to use a Gaussian approximation for the central 98% of the projected angular distribution, with a width given by

$$\theta_0 = \frac{13.6\ {\rm MeV}}{\beta c p}\ z\ \sqrt{x/X_0}\Big[1 + 0.038\ln(x/X_0)\Big]\ .$$