Radiation Detector 2018/19 (SPA6309)

Particle Propagation 2

Cherenkov radiation

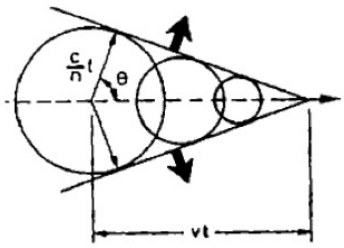

Fig. 2.9. Cherenkov radiation: an electromagnetic shock wave is formed when the particle travels faster than the speed of light in the same medium

Cherenkov radiation (Leo, 2.3)

Cherenkov radiation is the "shock wave" of an electromagnetic field. When the charged particles move faster than the speed of light in the medium: $v > \frac{c}{n}$, where "n" is the refraction of index. The opening angle of Cherenkov radiation is (2.57)

$$cos\theta_C = \frac{1}{\beta n},$$

here "β" is the relativistic beta ($= \frac{v}{c}$). If the beta is smaller than $\frac{1}{n}$, or energy of the particle is below **Cherenkov threshold**, $cos\theta_C > 1$ which means there is no emission. On the other hand, every **relativistic particle** (kinetic energy $>$ mass), $\beta \sim 1$. Thus you can assume opening angle of Cherenkov radiation is $\sim \frac{1}{n}$ for all relativistic particles.

For example, index of refraction of water is 1.33, so $\beta = 1/1.33$ is the threshold. Then Cherenkov threshold kinetic energy of e, μ, π^+, p are,

```
In [2]: import numpy as np
        beta=1.0/1.33
        gamma=1.0/np.sqrt(1-beta**2)
        print "T(e)=",0.511*(gamma-1),"MeV"
        print "T(mu)=",106.6*(gamma-1),"MeV"
        print "T(pi)=",139.6*(gamma-1),"MeV"
        print "T(p)=",938*(gamma-1),"MeV"
```

```
T(e)= 0.264064080855 MeV
T(mu)= 55.0865577674 MeV
T(pi)= 72.1396197404 MeV
T(p)= 484.720367597 MeV
```

By using this, one can distinguish different particles (**particle identification** or **PID**). If a 60 MeV kinetic energy particle, either muon or pion, enter the water and emit Cherenkov radiation, you know it is muon.

Radiation loss vs collision loss

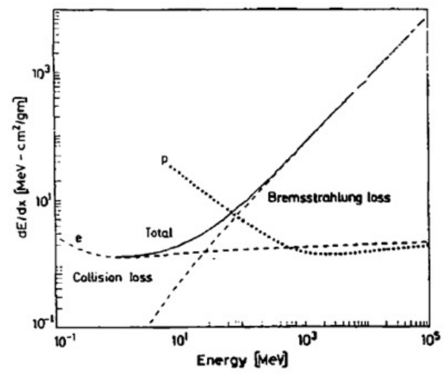

Fig. 2.10. Radiation loss vs. collision loss for electrons in copper. For comparison, the dE/dx for protons is also shown

Energy loss of electrons and positrons (Leo, 2.4)

Since the main energy loss process is ionization (=interaction with atomic electrons), the energy loss of electrons and photons need special treatment. For an electron, ionization means collision with other electrons and let's call it a collision term. The total energy loss is collision loss term + radiative loss term (eq. 2.65).

$$E_c \sim \frac{800\,MeV}{Z + 1.2}$$

After traveling **radiation length** or L_{rad}, an electron loses 36.8% of energy.

$$E(x) = E_o exp(\frac{-x}{L_{rad}})$$

The radiation length of a material with atomic number z, mass number A, and density $\rho(g/cm^3)$ is roughly (eq. 2.82),

$$L_{rad} = \frac{716.4 g/cm^2 \times A}{\rho z(z+1) ln(287/\sqrt{z})}$$

Shorter radiation length means an electron loses all energy in short distance, and all energy would be measurable by a small detector because they are "contained". Lead is commonly used to stop electrons because of large atomic number and density.

Interaction of Photons (Leo, 2.7.3, 2.7.4)

The 3 main interaction processes of photons are

1. photoelectric effect (at low energy)
2. Compton scattering (at medium energy)
3. pair creation (at high energy)

The photoelectric effect is the absorption of a photon by an atomic electron. Compton scattering is the scattering of a photon by an atomic process. Both are dominant process for <1 MeV. To create an electron-positron pair, a photon needs at least 1.022 MeV total energy. In this context 1 MeV photon is already "high energy" and we discuss mostly the energy region higher than 1 MeV.

An important concept is the mean free path of pair production or **pair conversion length** λ_{pair}. This is the distance for 36.8% of photons to cause pair creation by propagating in a material. By a good approximation,

$$\lambda \sim L_{rad}$$

Therefore, heavy element, such as lead, is good to produce electrons by pair creation, and stop electrons.

If a high-energy photon enters a material, it creates electron-positron pairs, then they cause radiative loss and produce many photons which also produce electron positrons pair... this process is called **electromagnetic shower**. The width of the shower is described by **Moliere radius** (eq. 2.131),

$$R_M = L_{Lad}\frac{21.2\,MeV}{E_c}$$

Therefore, the shape of an electromagnetic shower is predictable, and the detector has to be big enough to stop all electrons and positrons in it. By summing up all energy, you can estimate the energy of photon or electron or positron entered in the detector. Such a detector measuring the total energy of every particle to estimate the energy of an incoming particle is called **calorimeter**. Here, we are talking more specifically, **electromagnetic calorimeter.** The electromagnetic calorimeter is also useful to distinguish electrons and photons from MIP.

For a large **detector system** of collider experiments, many detectors are combined. For example, there are detectors to measure tracks of MIP (silicon tracker, muon system, etc), and there are calorimeters to measure total shower energy (EM calorimeter, hadronic calorimeter, etc).

Interaction of Neutrons (Leo, 2.8)

Interaction of neutrons are important for nuclear fission reactors, especially how to slow down neutrons is a key parameter for reactors. Importantly, neutrons lose kinetic energy mainly by elastic collision with nuclei, but maximum energy neutrons can transfer depend on atomic number A. For a neutron with energy E_0, neutron energy E after a collision with nucleus A is,

$$\left(\frac{A-1}{A+1}\right)^2 E_0 < E < E_0.$$

Thus, if $A = 1$, there is a chance the neutron loses all energy by 1 collision, but if the target nuclei are large, then neutrons don't lose much energy by each collision. This principle is applied to the choice of **moderator** for fission reactors, where light elements (carbon, water) are often prefered.