PHYS 312 **High energy particle detection** **Spring 2007**

1. Interactions of high-energy particles with matter and their detection.

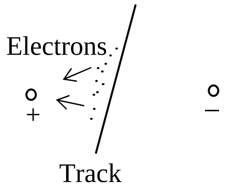
a) Ionization energy loss

Any charged high-energy particle traveling through matter looses energy by Coulomb interaction with electrons in the material. Most of this energy goes into ejecting electrons bound in atoms and producing ions and free electrons. The amount of energy loss is proportional to the density of the material and is only weakly dependent on the particle energy or type of the material. Numerically dE/dx ~ 1 MeV/cm ρ (g/cm^3), so in a typical solid material particles loose several MeV per cm of travel, while in air (ρ=0.0012g/cm^3) they loose about 0.1 MeV/m.

Several types of detectors are based on measuring the ionization energy deposited in the material:

Ionization counters and drift chambers

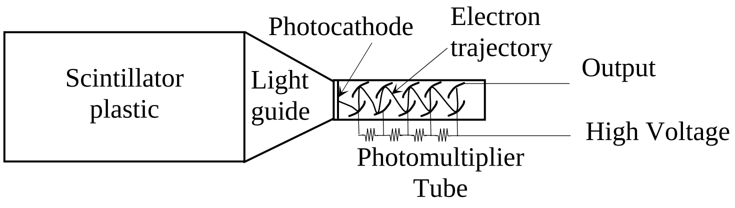
These detectors consist of a tank filled with argon or other suitable gas and many thin wires with a high voltage (about 5 kV) applied between them. Electrons from the ionization track left by the high-energy particle drift to the closest wire, get amplified by electrical breakdown in the high electric field near the wire, and generate an electric current in the wire. The time of signal arrival depends on the distance from the track to the wire.



Scintillation counters

These detectors typically consist of a transparent plastic material, such as Lucite, with a special chemical called "wavelength shifter". In a solid material the electrons and ions produced by the high-energy particle recombine and emit photons in the ultra-violent wavelength range. These photons cannot travel very far, but the wavelength shifter absorbs the photons and reemits them in the visible range. The visible photons travel through the plastic to a photomultiplier tube which converts them to an electrical signal.

Photomultiplier tubes are based on the photoelectric effect. Each photon ejects a single electron from the photocathode. This electron is accelerated by an electric field to secondary electrodes called dynodes where it ejects several additional electrons. With many dynodes a large amplification factor is achieved, resulting in a strong electrical pulse at the output. However, the efficiency of converting the initial photon into an electron, known as quantum efficiency, is typically not very high, on the order of 10%.



Avalanche photodiodes

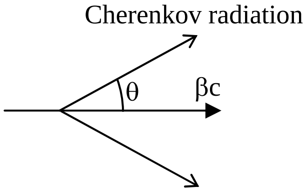
These photodiodes serve the same function as photomultiplier tubes, converting a single photon into a large electrical signal. They work by using a p-n junction with very large reverse bias voltage (100-1000 V). The electron-hole pair created by the absorption of the initial photon is accelerated by the electric field and generates additional electron-hole pairs. Unlike photomultiplier tubes, avalanche photodiodes can have quantum efficiency in excess of 80%.

Silicon strip detectors

These detectors consist of long silicon p-n junctions. The ionization track generates an electric current that is amplified by electronics which is often placed on the same piece of silicon.

b) Cherenkov Radiation

If a charged particle travels at a speed greater than the speed of light in a given medium it emits Cherenkov radiation. Recall that the speed of light in a transparent medium is $v = c/n$ where the index of refraction $n = 1.3 - 1.5$ for glass or water. High energy particles with total energy much greater than their rest mass travel nearly at the speed of light. The Cherenkov radiation is similar to the sound shock wave created by an object traveling faster than the speed of sound. The Cherenkov radiation is emitted at an angle $\cos\theta = 1/\beta n$ to the path of the particle. This direction and opening angle of the Cherenkov radiation cone can be used to determine the speed and direction of the particle. The Cherenkov radiation in the blue part of the visible spectrum is commonly detected using arrays of photomultiplier tubes.



c) Bremsstrahlung radiation

This “braking” radiation is emitted when a charged particle is accelerated in the Coulomb field of a nucleus. The amount of energy loss per unit length is proportional to the energy of the particle and inversely proportional to the square of the particle rest mass. As a result, the energy of the particle decays exponentially with distance $E(x) = E_0 \exp(-x/X_0)$, where X_0 is so-called radiation length. The radiation lengths are shown in the table on the right for electrons and muons. Muons can propagate much further then electrons because of their larger mass. Hadrons (mesons and baryons) are also absorbed in a heavy material due to strong interactions with the nuclei.

	Electron	Muon	Proton
Air	250 m	10,000 km	700 m
Lead	0.4 cm	175 m	16 cm

Calorimeters

These detectors measure the total energy of a high-energy particle by absorbing all secondary particles that it produces while it looses energy. Calorimeters work particularly well for measuring the total energy of electrons, since they loose all their energy in a few cm of a heavy material like lead. The bremstrahlung photons emitted by the primary electron are converted to electron-positron pairs and their energy is also easily absorbed. A photomultiplier typically measures the total amount of light generated by all particles in such electromagnetic shower. Hadronic calorimenters can also be constructed although they have to be larger than electromagnetic calorimeters and have poorer energy resolution. Calorimeters are typically constructed from lead-doped glass or sandwiches of lead and scintillator material.

2. General experimental techniques

a) Bending in a magnetic field.
Charged particles are bend in a uniform magnetic field B by the Lorentz force such that the radius of curvature $R = cp/qB$, where p is the relativistic momentum of the particle perpendicular to the magnetic field and q is its charge. High-energy detectors commonly use a large magnet and a collection of tracking detectors inside the magnetic field to measure the radius of curvature and hence the momentum of the particle.

b) Coincidence techniques.
Since high-energy particles move with speeds close to the speed of light it is easy to calculate how long it takes them to get from one part of the detector to another. One can then identify signals in each detector that are separated by the appropriate time difference and associate them with the same particle. In this matter individual detector hits are reconstructed into tracks of particles going through the whole detector. Coincidence techniques are also useful for eliminating spurious signals due to cosmic rays or electronic noise.