PHYS 210
Spring 2006
High-Energy Physics Experimental Techniques

1. One-page review of high energy physics

Recall that atoms are made of electrons, which are elementary particles, and nuclei, which consist of roughly equal numbers of protons and neutrons. Protons and neutrons, in turn, are made from three quarks, which are also believed to be elementary particles. In addition to these common stable particles there is a number of unstable elementary particles and many more composite particles. Some of them are listed with a few of their properties in the table below. See attached chart of fundamental particles and interactions for more information.

Name	Composition	Mass	q (e)	Lifetime	Decays	Notes
Electron (e)	Lepton (elem.)	0.5 MeV	-1	Stable	None	
Muon (μ)	Lepton (elem.)	105 MeV	-1	2.2 μsec	$e\nu_e\nu_\mu$	Secondary cosmic rays
Tau (τ)	Lepton (elem.)	1777 MeV	-1	2.9×10^{-13} sec	$\mu\nu_\tau\nu_\mu$	Many other decay modes
Neutrinos (ν_e, ν_μ, ν_τ)	Leptons (elementary)	$0<m_\nu<2$ eV	0	Stable	Change flavors	Non-zero mass only confirmed in the last year
Up (u)	Quark (elem.)	~ 3 MeV	2/3	Stable	None	Exist only bound inside baryons or mesons. Have one of 3 different "colors" – charges of the strong force
Down (d)	Quark (elem.)	~ 6 MeV	-1/3	10^{-8} sec to ∞[1]	$ue\nu_e$	
Strange (s)	Quark (elem.)	~100 MeV	-1/3	~10^{-8} sec	$ue\nu_e$	
Charm (c)	Quark (elem.)	1200 MeV	2/3	~10^{-12} sec	$se\nu_e$	
Bottom (b)	Quark (elem.)	4200 MeV	-1/3	~10^{-12} sec	$ce\nu_e$	
Top (t)	Quark (elem.)	174 GeV	2/3	~10^{-24} sec	$be\nu_e$	Discovered in 1995
Proton (p)	Baryon (uud)	938 MeV[2]	1	Stable	None	Primary cosmic rays
Neutron (n)	Baryon (udd)	939 MeV[2]	0	887 sec	$pe\nu_e$	Stable inside nuclei
Pion (π^+)	Meson ($u\bar{d}$)	139 MeV[2]	1	2.8×10^{-8} sec	$\mu^+\nu_\mu$	
Kaon (K^+)	Meson ($u\bar{s}$)	493 MeV[2]	1	1.2×10^{-8} sec	$\mu^+\nu_\mu$	

Notes to Table: All particles have corresponding anti-particles with the same mass and opposite charge. 1 MeV = 1.8×10^{-30} kg. (1) Lifetime depends on binding inside mesons or baryons. All decays must satisfy conservation of energy, charge, baryon and lepton nmmber. (2) Masses of quarks do not add up to masses of baryons and mesons because of extra binding energy (mass) of the gluons holding them together.

The goal of modern particle physics experiments is to search for new, heavier particles and to make precision measurements of properties of the known ones in a quest to arrive at a complete picture of fundamental interactions. For example, it is believed that there is an additional elementary particle called Higgs boson with a mass in excess of 115 GeV whose interactions are responsible for giving mass to all other particles. Additional elementary particles, called supersymmetric partners (one for every known elementary particle) are believed to exist in the mass range of 200 to 1000 GeV. Another active area of research is violation of CP (charge-parity) symmetry that is related to the origin of asymmetry between matter and anti-matter in the Universe.

Most high-energy experiments are performed at large accelerators (construction cost >b$) in collaborations of ~1000 physicists, although smaller teams and even table-top experiments addressing specific questions of particle physics also exist.

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

The purpose of high-energy particle detectors is to track particles produced in a high-energy collision and measure their properties, such as energy, momentum, charge and mass.

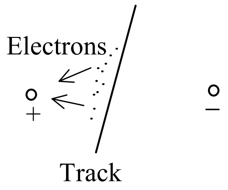
a) Ionization energy loss

Any charged high-energy particle traveling through matter looses energy by electromagnetic interactions with electrons in the material. Most of this energy goes into kicking off 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 $dE/dx \simeq 1$ 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 0.1 MeV/m.

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

Ionization counters and drift chambers

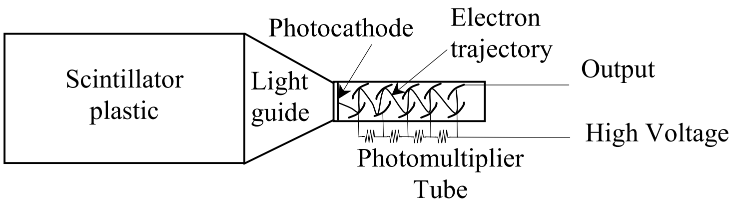
These detectors consist of a tank filled with argon or other suitable gas and many thin wires with a high voltage (about 5 kV) applied between them. Electrons from the ionization track left by the high-energy particle drift to the closest wire, get amplified by electrical breakdown in the high electric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

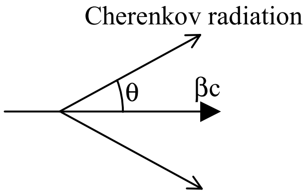


Silicon strip detectors

These detectors consist of long silicon p-n junctions, similar to solar cells we will discuss later in the class. The ionization track generates an electric current that is amplified by electronics located 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.

3. 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.

3. Cosmic Rays

We will use an easily available source of high-energy particles generated by cosmic rays. Cosmic rays are initially generated in intergalactic space by a process that is still not well understood. One plausible mechanism is acceleration by shock waves in supernova star expositions. Cosmic rays have a wide range of energies from a few GeV to over 10^{20} eV, 11 orders of magnitude higher than the highest energy achieved on Earth. The primary cosmic rays consist mostly of protons. They interact in the upper atmosphere (absorption length = 700 m) generating a hadronic shower consisting primarily of pions. Pions decay to muons, which have a much longer lifetime and absorption length, and so are able to reach the Earth surface. It takes muons on the order of 100 μsec to reach the Earth surface, while their lifetime is 2.2 μsec. They don’t decay because of relativistic time dilation. The flux of muons reaching the surface is about $100/m^2/sec$ and they have an average energy of 2 GeV.