Detector types

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Overview of particle detectors

- What do the particle detectors measure?
  - spatial location
    - a charge particle moving in magnetic field → momentum
      $$p = qBR$$
    - position of production and decay points ("vertices")
  - energy
  - time of flight (→ velocity)
    $$v = p/E$$
- Particle mass needed for particle identification is not measured directly

$$m = \sqrt{E^2 - p^2}$$

Detector characteristics

- Type of detected particles
  - many detectors are only able to detect one type of particles, or certain set of types, e.g. charged particles
- Spacial resolution
  - for the purposes of vertex reconstruction and curvature measurement, need very good position resolution
  - for the "triggering" purposes, detector size is enough
- Sensitivity
  - quantum efficiency: fraction of particles which get registered
  - potentially want to detect each particle, but sometimes detecting a bunch of particles as a single object is enough
- Energy (or momentum) range
- Energy (or momentum) discrimination
- Speed
  - real time detectors: have finite recovery time
  - some detectors can't be used for real time measurements at all

Natural detectors: a human eye

- detected particles: photons
- sensitivity: high, single photons
- spatial resolution: high, few microns
- dynamic range: high, $1 - 10^{14}$
- energy range: limited, visible light
- energy discrimination: good, 10^7 colors
- speed: fare, ~ 10 Hz (but this includes pattern recognition)

Photographic paper

W. C. Röntgen (1895, Nobel prize: 1901): detected high energy photons (X-rays) invisible to the eye

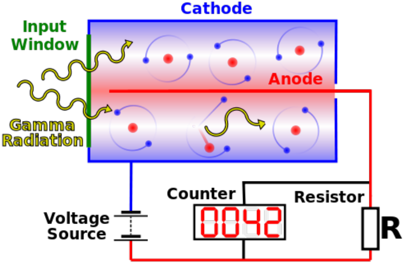
- detected particles: photons
- sensitivity: fair, quantum efficiency $\sim 10^{-2}$
- spatial resolution: high, $\sim 10^{-5}$ μm
- dynamic range: fair
- energy range: good
- energy discrimination: fair
- speed: none, no real time resolution

Photographic emulsion

- inherited problems of photographic paper – no time resolution and complicated read out
- today the images are read out using special pattern recognition programs – makes emulsions more practical
- one advantage of emulsions is their excellent spatial resolution ($< 1\ \mu$m)
- emulsions were used by the DONUT experiment to discover the τ-neutrino (2000)

The Geiger counter

H. Geiger (1908): passing charged particles ionize gas, ions/electrons drift towards cathode/anode, cause electric pulse



- detected particles: charged particles (electrons, α)
- sensitivity: single particles
- spatial resolution: size of the detector (fix: multiple anodes)
- dynamic range: none (fix: proportional chambers)
- speed: high, determined by charge drift velocity

The cloud chamber

C. T. R. Wilson (1911, Nobel prize: 1927)

- the first tracking detector (= several measured points per particle trajectory)
- principle of operation:
  - an air volume is saturated with water vapor
  - pressure lowered to generate super-saturated air
  - charge particles cause saturation of vapor into small droplets which can be observed as a "track"
- a cloud chamber is not difficult to be made in a classroom
  - need an aquarium, a light source, isopropyl alcohol, and dry ice
- can observe cosmic muons by a naked eye

The cloud chamber (2)

- detected particles: charged particles
- sensitivity: high, single particles
- spatial resolution: fair, $10^{-3} - 10^{-4}$ m
- dynamic range: good (distance between droplets, curling tracks in magnetic field)
- speed: fair, seconds

Anderson (1932, Nobel prize: 1936) used the cloud chamber to discover the positron

The bubble chamber

D. A. Glaser (1952, Nobel prize: 1960)

- popular in 70's, an improvement over the cloud chambers
- principle of operation:
  - a liquid is heated near the boiling point
  - a pressure is suddenly dropped, so the liquid becomes superheated
  - particles entering the chamber create a track of micro bubbles
- the first particle detector that required a trigger

Gargamelle: a giant (12 m^3) bubble chamber at CERN used to discover neutral currents

Modern detector types

- Tracking detectors detect charged particles
  - principle of operation: ionization
  - two basic types: gas and solid
- Scintillators
  - sensitive to single particles
  - very fast, useful for online applications
- Calorimeters
  - measure particle energy
  - usually measure energy of a bunch of particles ("jet")
  - modest spatial resolution
- Particle identification systems
  - recognize electrons, charged pions, charged kaons, protons

Tracking detectors

- A charged track ionizes the gas
    - $10 - 40$ primary ion-electron pairs
    - multiplication $\times 3 - 4$ due to secondary ionization
    - typical amplifier noise 1000 e^-
        - the initial signal is too weak to be effectively detected!
    - as electrons travel towards cathode, their velocity increases
        - electrons cause an avalanche of ionization (exponential increase)
- The same principle (ionization+avalanche) works for solid state tracking detectors
    - dense medium → large ionization
    - more compact → put closer to the interaction point
    - very good spatial resolution

Calorimetry

- The idea: measure energy by total absorption
    - also measure location
    - the method is destructive: particle is stopped
    - detector response proportional to particle energy
- As particles traverse material, they interact producing a bunch of secondary particles ("shower")
    - the shower particles undergo ionization (same principle as for tracking detectors)
- It works for all particles: charged and neutral

Electromagnetic calorimeters

- Electromagnetic showers occur due to
  - Bremsstrahlung: similar to synchrotron radiation, particles deflected by atomic EM fields
  - pair production: in the presence of atomic field, a photon can produce an electron-positron pair
  - excitation of electrons in atoms
- Typical materials for EM calorimeters: large charge atoms, organic materials
  - important parameter: radiation length

Hadronic calorimeters

- In addition to EM showers, hadrons (pions, protons, kaons) produce hadronic showers due to strong interaction with nuclei
- Typical materials: dense, large atomic weight (uranium, lead)
  - important parameter: nuclear interaction length
- In hadron shower, also creating non detectable particles (neutrinos, soft photons)
  - large fluctuation and limited energy resolution

Muon detection

- Muons are charged particles, use tracking detectors to detect them
  - Calorimetry does not work – muons only leave small energy in the calorimeter (said to be "minimum ionization particles")
  - Muons are detected outside calorimeters and additional shielding, where all other particles (except neutrinos) have already been stopped
- As this is far away from the interaction point, use gas detectors

Detection of neutrinos

- In dedicated neutrino experiments, rely on their interaction with material
    - interaction probability extremely low → need huge volumes of working medium
- In accelerator experiments, detecting neutrinos is impractical → rely on momentum conservation
    - electron colliders: all three momentum components are conserved
    - hadron colliders: the initial momentum component along the (anti)proton beam direction is unknown

Multipurpose detectors

- Today people usually combine several types of various detectors in a single apparatus
  - goal: provide measurement of a variety of particle characteristics (energy, momentum, flight time) for a variety of particle types (electrons, photons, pions, protons) in (almost) all possible directions
  - also include "triggering system" (fast recognition of interesting events) and "data acquisition" (collection and recording of selected measurements)
- Confusingly enough, these setups are also called detectors (and groups of individual detecting elements of the same type are called detector subsystems)

Generic HEP detector