CHAPTER 7

Particle Detection

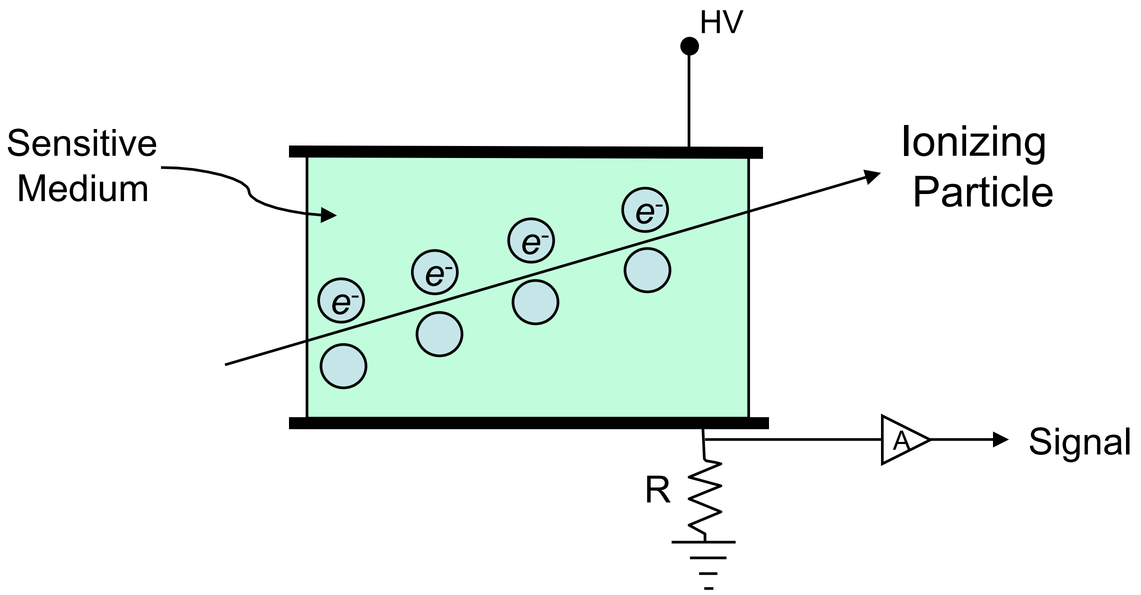
Lecture Notes For
PHYS 415
Introduction to Nuclear and Particle Physics

To Accompany the Text
Introduction to Nuclear and Particle Physics, 2nd Ed.
A. Das and T. Ferbel
World Scientific

Introduction

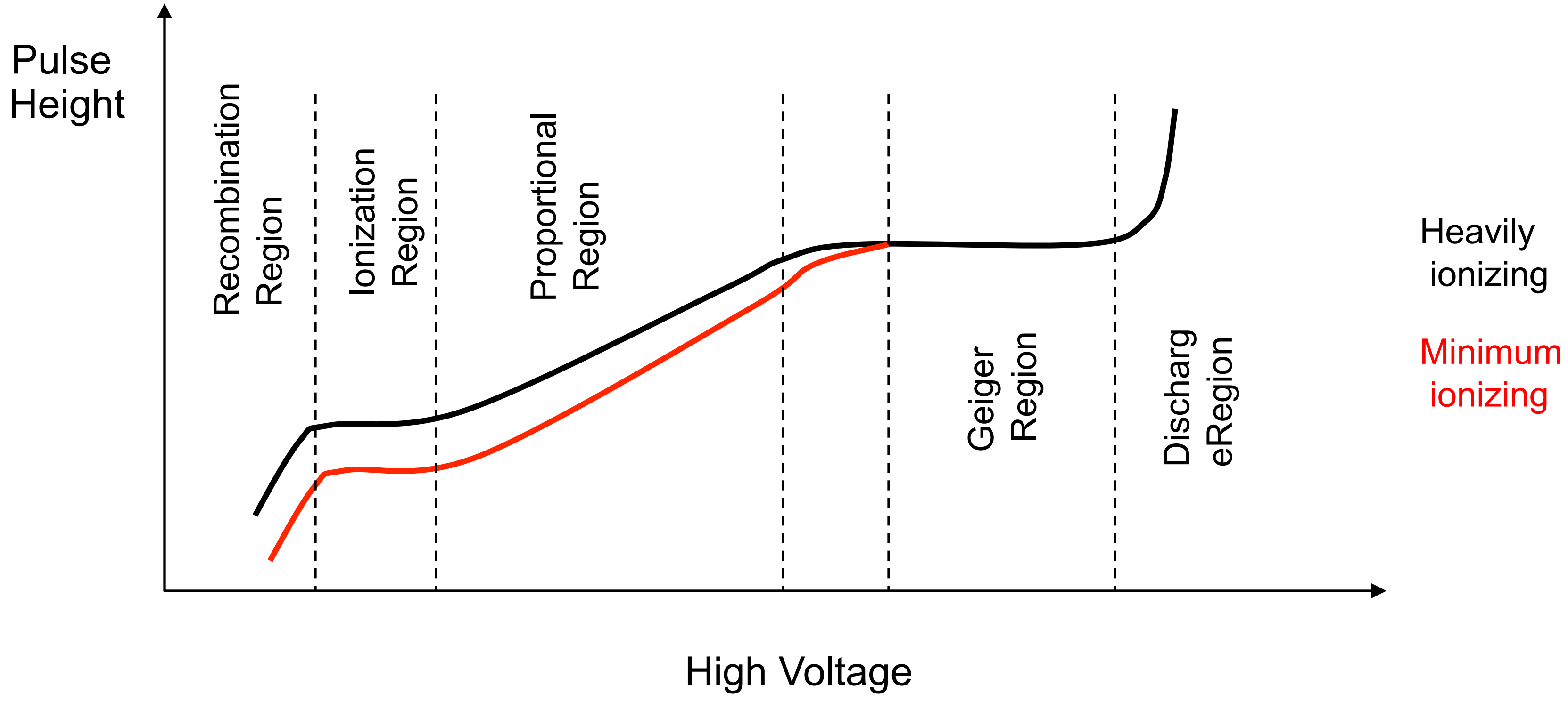
- Discerning the nature of particles and their interactions requires detection of reaction products.
- Particles are too small to be seen directly, but they leave traces when they interact with matter.
- The principles of the previous chapter will be exploited to describe how particle detectors function.
- The basic detectors described here employ the same principles as modern nuclear and high energy experiments.

Ionization Detectors



- High energy particle ionizes medium within detector
- Medium: easily ionized and chemically inert
- HV: separates charges to prevent recombination
- Signal may depend on amount of deposited energy …

Operating Conditions vs. Voltage



- Proportional Region: signal is proportional to initial ionization.
- Geiger Region: *avalanche* occurs and signal is independent of initial ionization

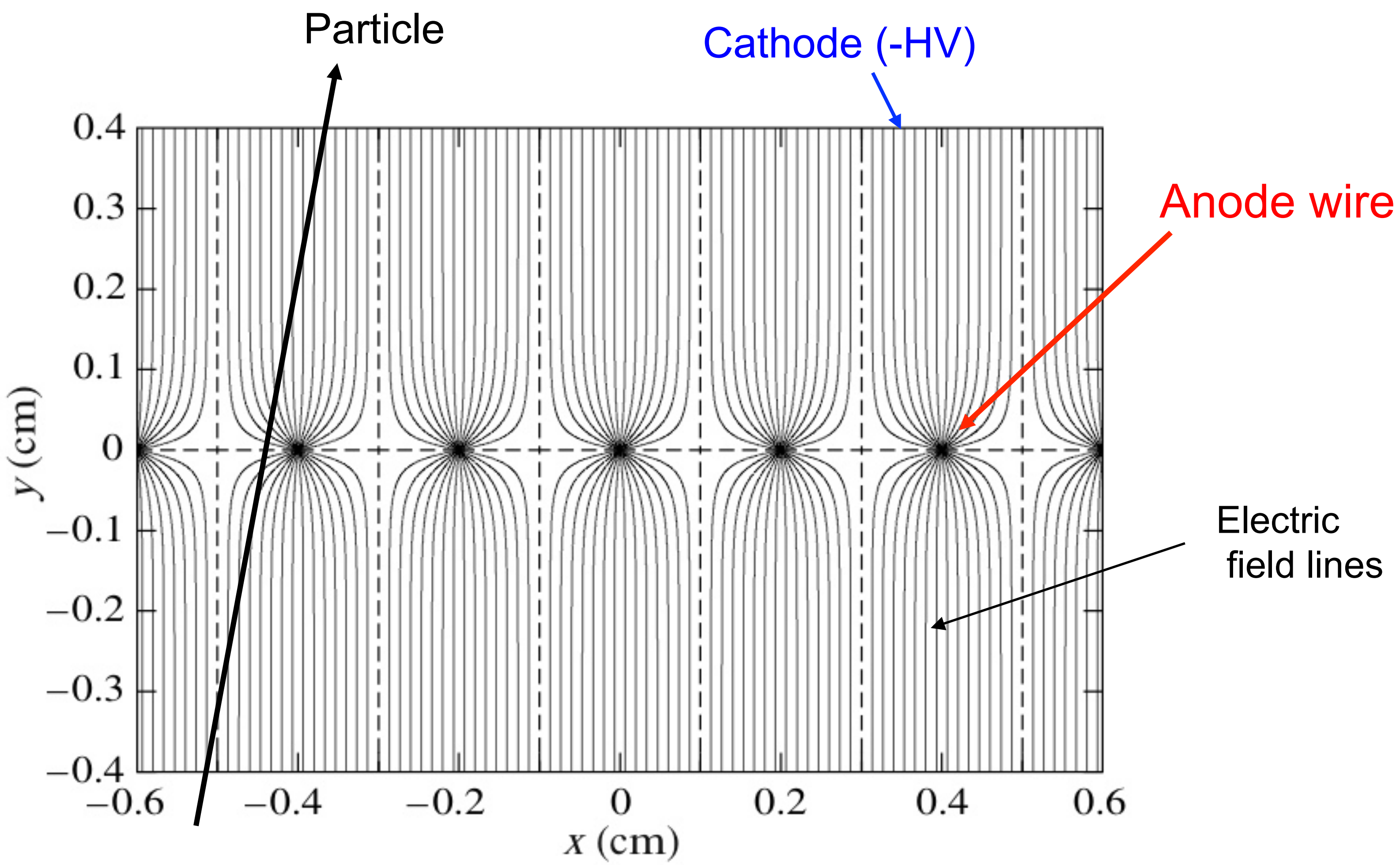
Ionization Counters

- Charge in signal pulse is proportional to energy deposited.
  - Good energy resolution, limited only by electronic noise and statistics of initial ionization.
  - Fast recovery time ⇒ good for high rates.
  - But, must use low-noise amplifiers for minimum-ionizing particles at low rate.
- For high rates, integrated signal can be used to determine rate of incident radiation (high radiation area monitors).

Proportional Counters

- Thin anode wires (10-50 μm): high electric fields near the wires.
- As electrons from primary ionization approach the wire, secondary ionization occurs.
  - Each electron gains enough energy between collisions to cause ionization.
  - This results in an avalanche and detectable current pulse on the anode wire.
- A series of proportional counters can be made from a single plane of wires, enlarging the detection area.
- Each cell of a Multi-Wire Proportional Chamber (MWPC) acts as an independent proportional counter.

The Multi-Wire Proportional Chamber (MWPC)

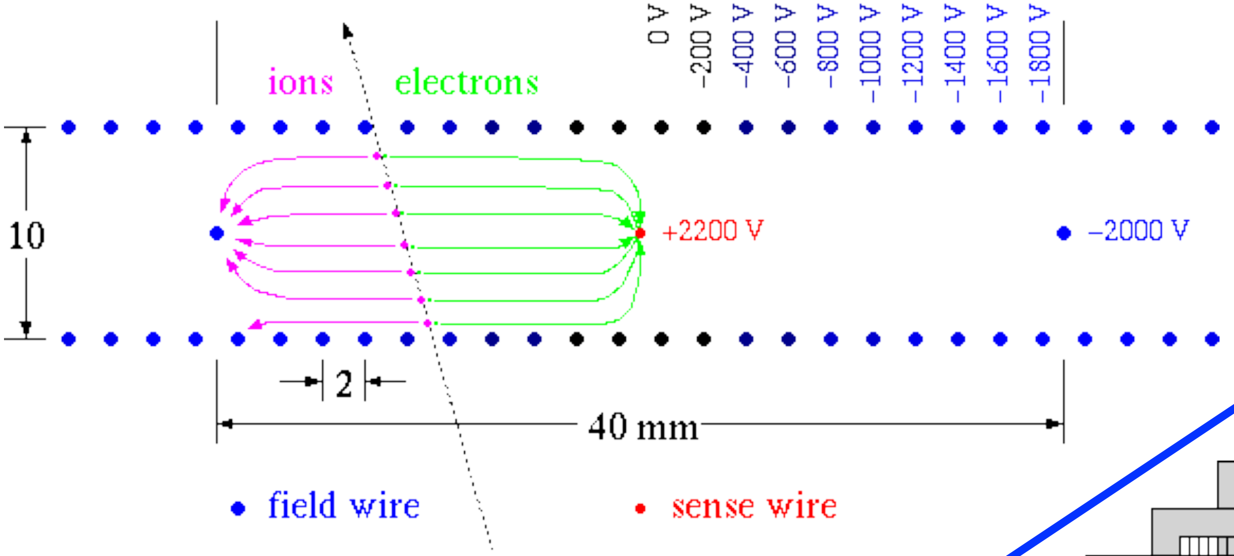


From http://pdg.lbl.gov/2005/reviews/pardetrpp.pdf

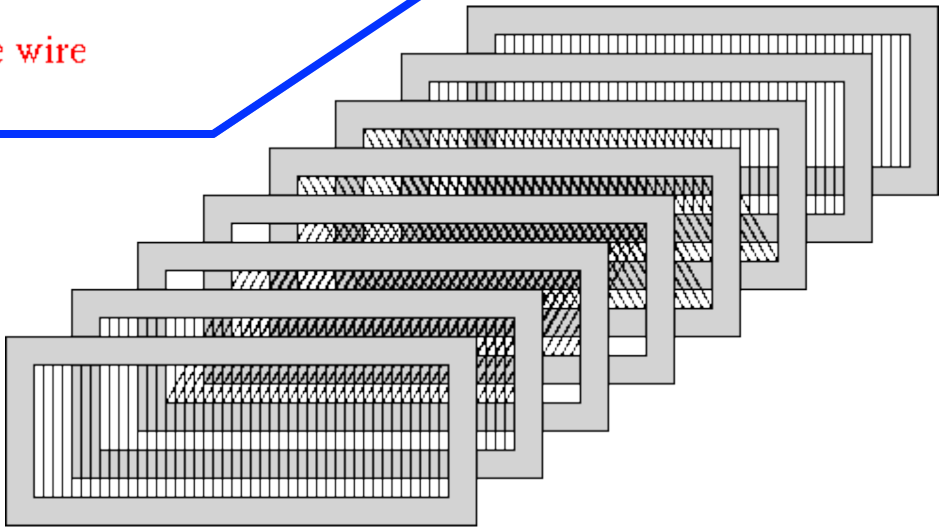
Drift Chambers

- By measuring the arrival time, relative to some fiducial time (set by the experimental **trigger**), of the current pulse(s), we can determine the distance of closest approach to the wire and improve the spatial resolution.
- Field-shaping wires can be used to ensure relatively uniform electric field. This simplifies deducing distance of closest approach from arrival time of signal.
- Resolutions of ~200 μm can be obtained, a factor of ten or so better than the wire spacing.

Drift Chambers



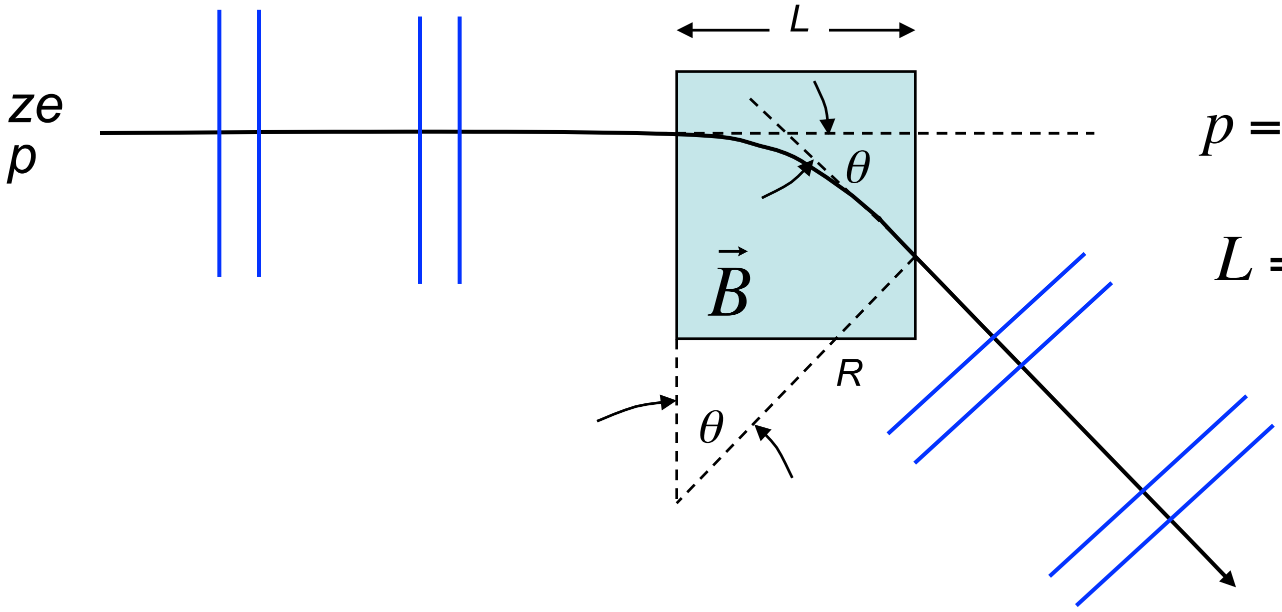
Field shaping wires give uniform field, except near the sense wire.



By stacking several chambers, 3 -dimensional information on the particle track can be obtained.

From http://ikpe1101.ikp.kfa-juelich.de/cosy-11/exp/drift_chambers/DriftChambers_E.html

Measuring Momentum using Magnetic Fields



$$p = \frac{RBze}{c}$$

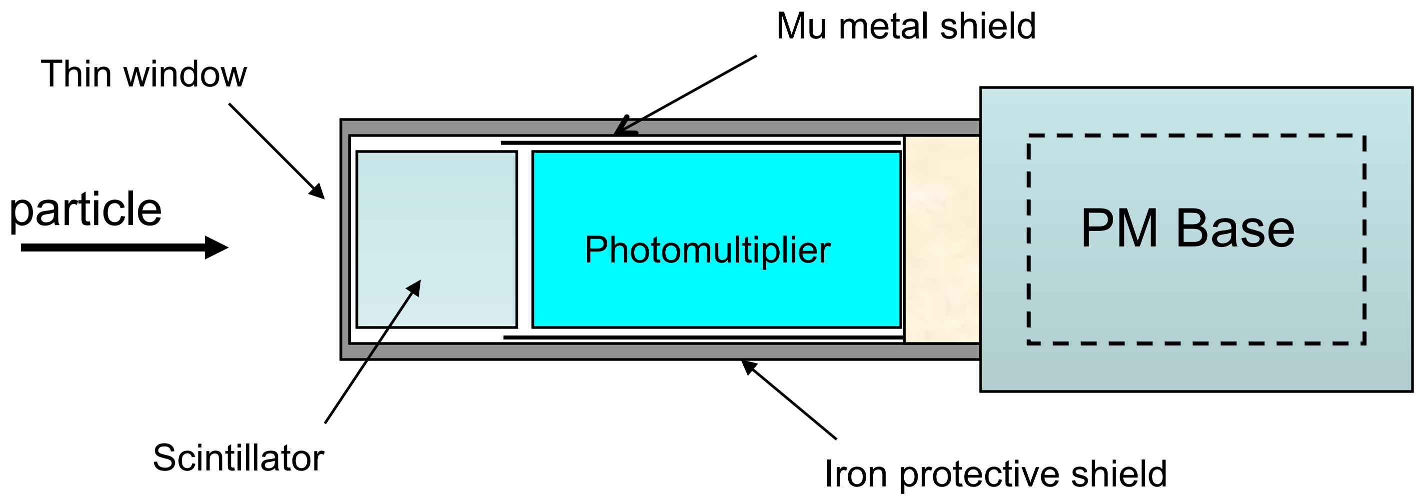
$$L = R\sin\theta$$

- Using tracking detectors before and after a magnetic field, we can measure the bend angle.
- In the simple case of a uniform field, the bend angle relates to the radius of curvature, *R*.
- From the known magnetic field and *R*, we can deduce the particle momentum.

Geiger Counters

- High operating voltage ⇒ avalanche.
- Number of electron-ion pairs is large ($\sim 10^{10}$), independent of particle energy loss.
- Resulting signals are large (~1V) and can be easily detected.
- However:
  - No information on particle energy or type.
  - Large ionization caused by avalanche implies relatively long recovery time ⇒ not suitable for high rate environments.

Scintillation Detectors



- Scintillator: converts particle energy to visible light.
- Photomultiplier: converts light to electron current (photoelectric effect) and amplifies current.
- PM Base: Provides resistive divider network to distribute HV to components of photomultiplier.

Ref: W.R. Leo, Techniques for Nuclear and Particle Physics Experiments, 2nd Edition, Springer-Verlag, 1994.

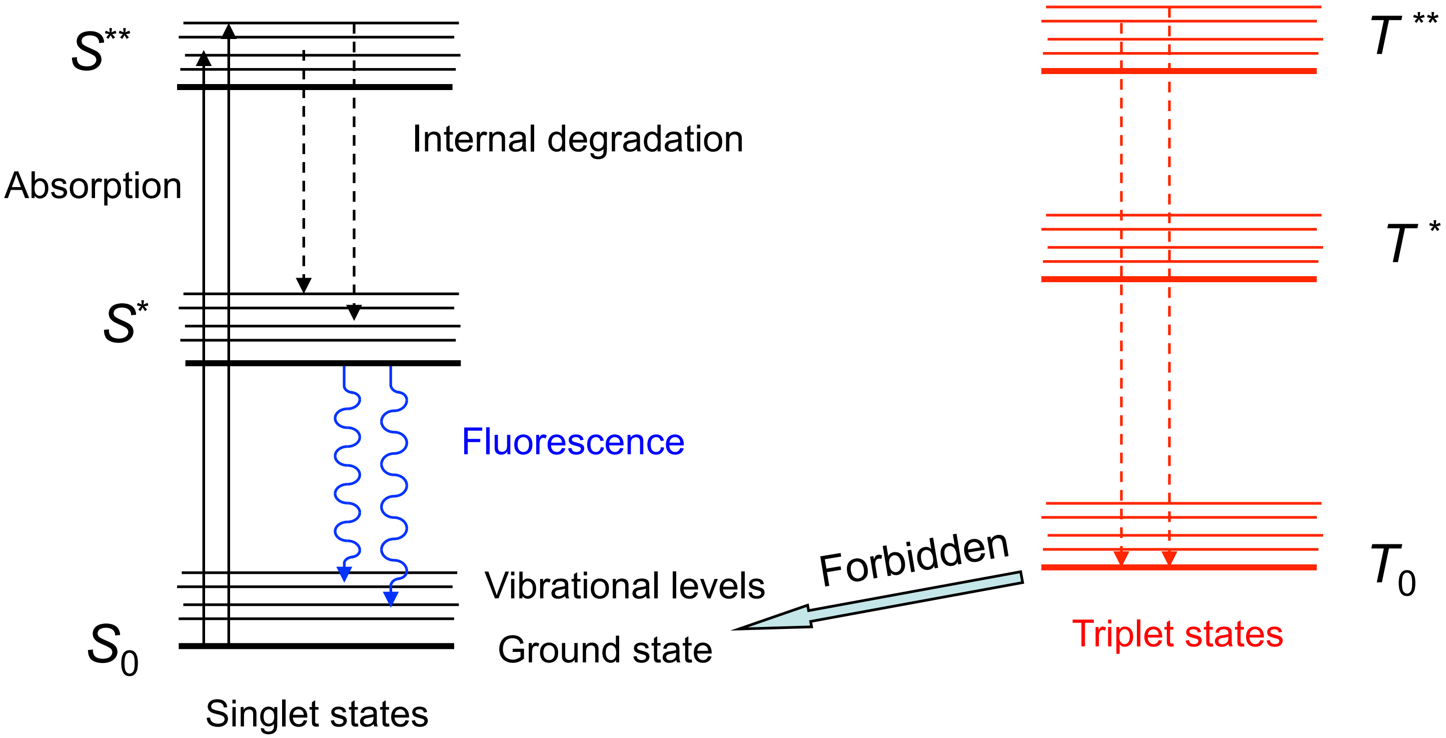
Scintillator Properties

- Sensitivity to Energy
  - Light output is roughly proportional to energy deposited.
  - Photomultiplier+base should be linear too.
- Fast Time Response
  - Gives precise time of particle arrival.
  - Fast recovery (low deadtime): good for high rate environments.
- Transparent to its own light.

Scintillator Materials

- Organic (organic crystals, liquids and plastic)
  - Fast time response: few ns
  - Typically produce UV light
    - UV light has short attenuation length
    - Wave-shifter is mixed with scintillant to convert UV to visible light
- Inorganic Crystals (NaI, CsI, …)
  - Slower response: ~ 500 ns (except CsF: few ns)
  - Also doped, typically with Thallium
  - Denser ⇒ higher stopping power ⇒ more light output ⇒ better energy resolution
  - Hygroscopic: must be sealed

Basic Mechanism - Organic Scintillator



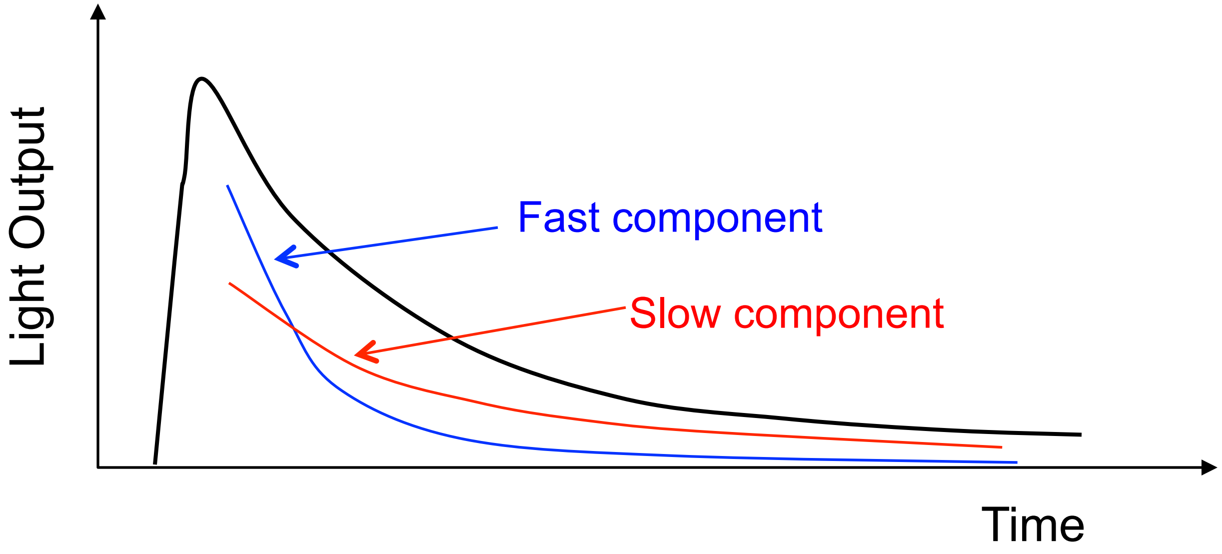
$$\boxed{S^{*} \rightarrow S_0 + \text{ photon}}$$

Fast component

$$\boxed{\begin{array}{l} T_0 + T_0 \rightarrow S^{*} + S_0 + \text{ phonons} \\ S^{*} \rightarrow S_0 + \text{ photon} \end{array}}$$

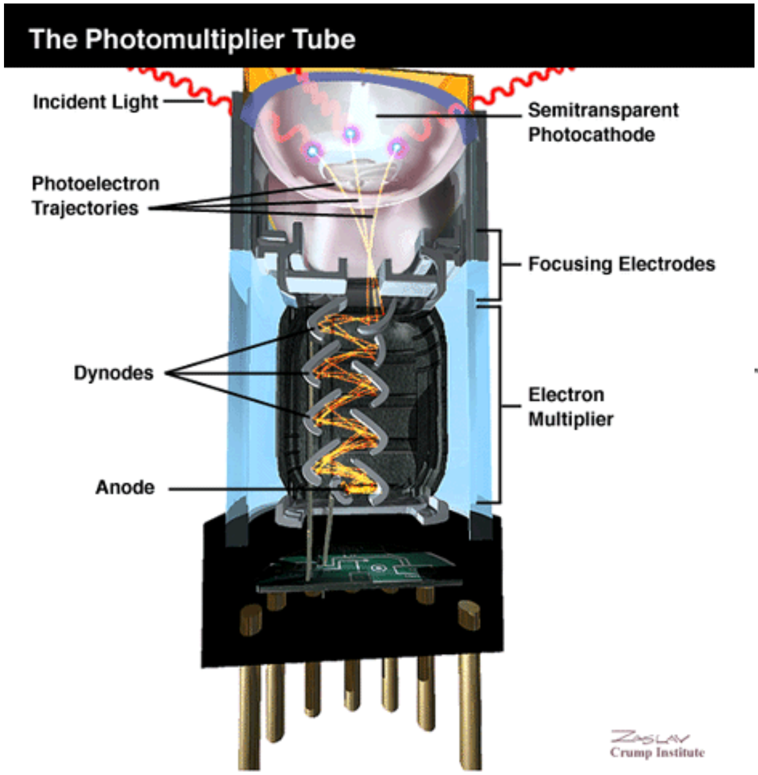
Slow component

Pulse Shape Discrimination

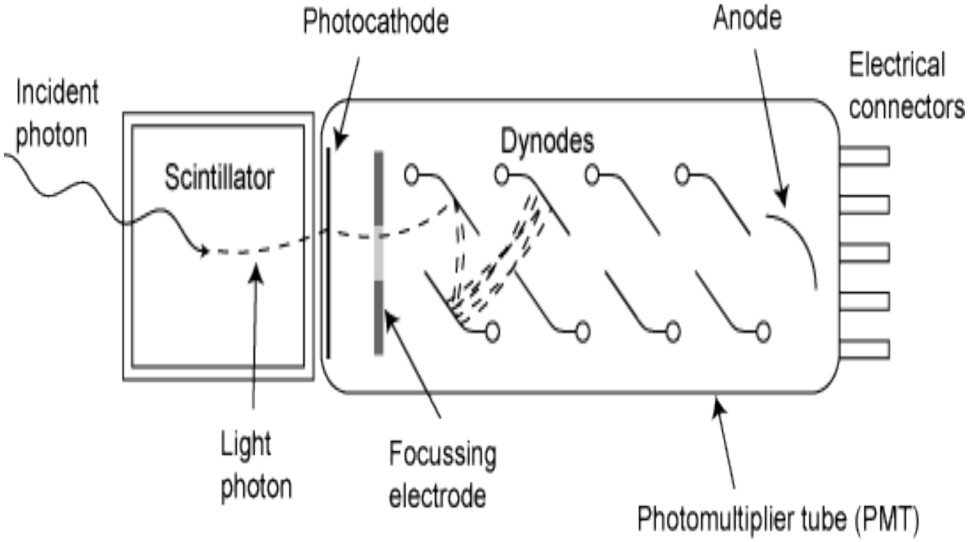


- Different types of particles deposit varying amounts of energy.
- Fast and slow components correspond to different excitations of molecule.
- Relative amounts of fast and slow components affect the overall pulse shape and this shape can be analyzed to determine particle type.

Photomultiplier Tube (PMT)



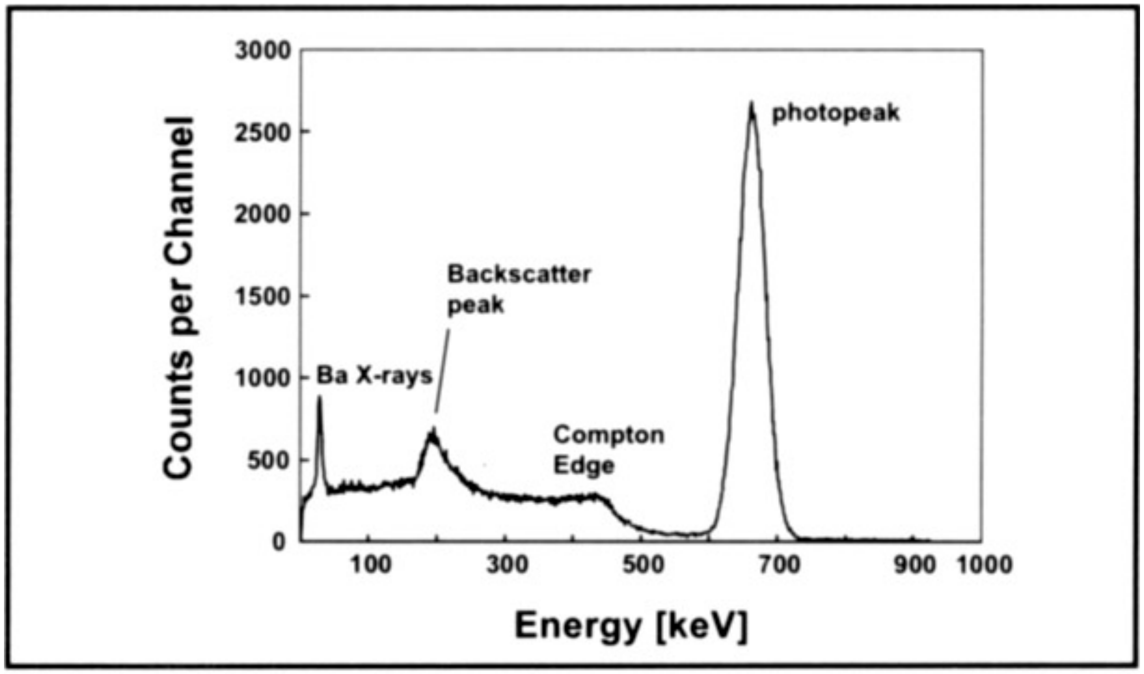
From: http://laxmi.nuc.ucla.edu:8248
/M248_99/autorad/Scint
/pmt_diagram.GIF



From: http://upload.wikimedia.org/wikipedia/en/b/b7
/Photomultipliertube.png

6-14 dynode stages with factor of 3-5 gain per stage ⇒ overall gain of 10^4 - 10^7

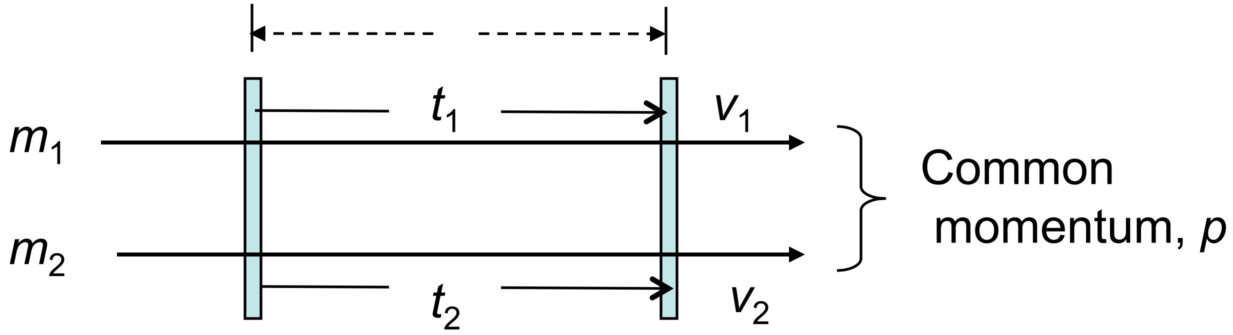
Gamma Ray Detection



Typical pulse height spectrum of radiation emitted generated by a ^{137}Cs source detected in a 76 x 76 mm NaI(Tl) scintillation crystal.

From http://www.scionixusa.com/images/misc/img003adj.jpg

Time-of-Flight



$$\Delta t = t_2 - t_1 = L\left(\frac{1}{v_2} - \frac{1}{v_1}\right) = L\left(\frac{E_2}{pc^2} - \frac{E_1}{pc^2}\right) = \frac{L}{pc^2}\left(\sqrt{m_2^2c^4 + p^2c^2} - \sqrt{m_1^2c^4 + p^2c^2}\right)$$

$$\Rightarrow \begin{cases} \dfrac{L}{p}\Delta m & \text{for } v_1, v_2 << c \\ \dfrac{Lc}{2p^2}\left(m_2^2 - m_1^2\right) & \text{for } v_1, v_2 \approx c \end{cases}$$

Time-of-Flight and Particle ID

- We want the best possible resolution in mass, so now assume that the masses (and velocities) are nearly equal. From the previous equations:

$$\frac{\Delta m}{m} = \begin{cases} \dfrac{v}{L}\Delta t & \text{for } m_1 \approx m_2 = m \quad \text{and } v_1 \approx v_2 = v << c \\ \dfrac{c\gamma^2}{L}\Delta t & \text{for } m_1 \approx m_2 = m \quad \text{and } v_1 \approx v_2 = v \approx c \end{cases}$$

- We see that the γ^2 factor makes the relativistic case more difficult.
- The resolution is obviously better for longer flight paths and better timing resolution.

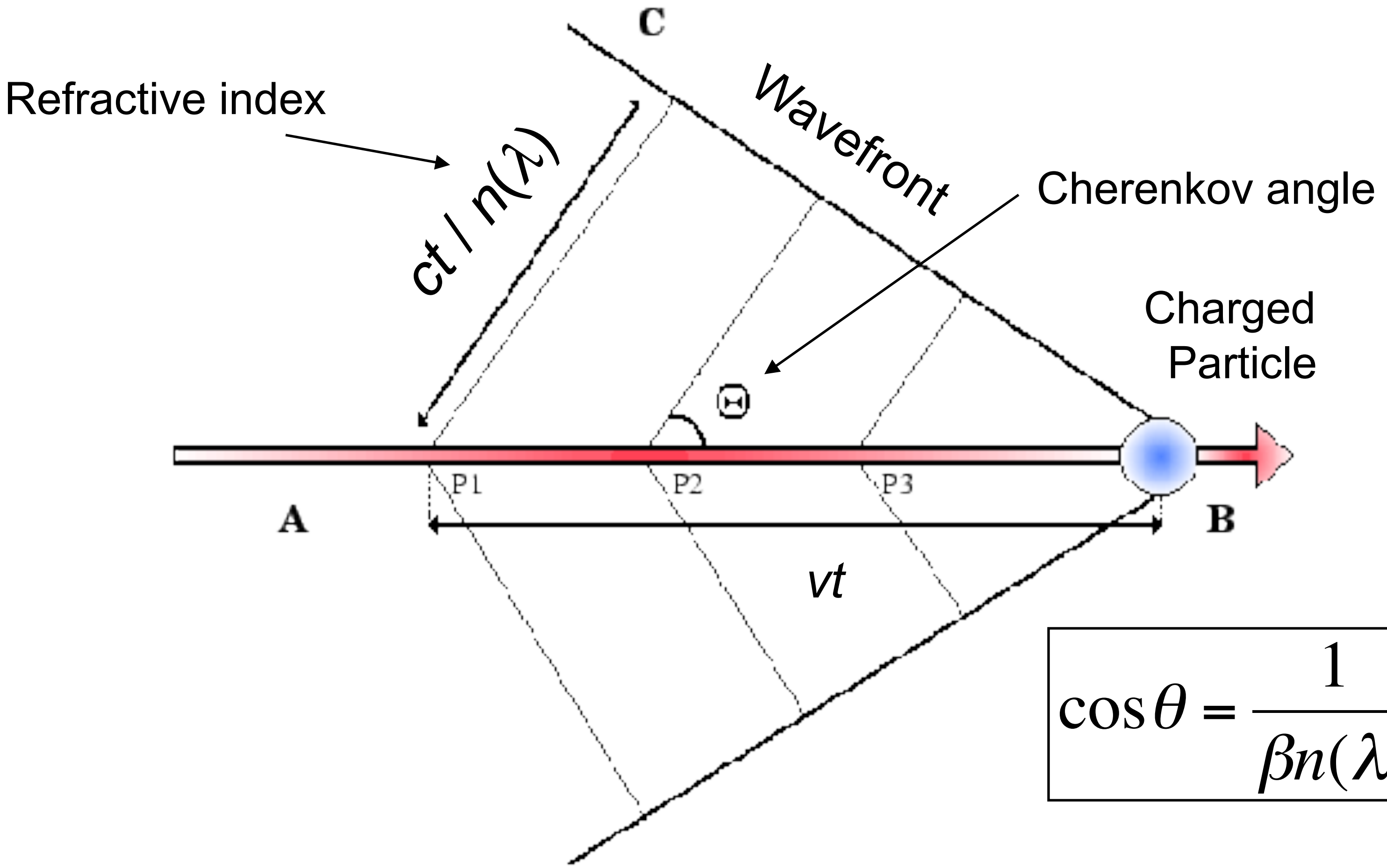
Cherenkov Detector

- If an energetic particle moves faster than the local light speed in a material, it will emit *Cherenkov* radiation. (The effect is analogous to a shockwave in the case of supersonic speed.)
- The angle of emission is given by

$$\cos\theta = \frac{1}{\beta n} \quad \text{where } n = \text{ index of refraction}$$

- The emission can only occur when $\beta > 1/n$.

Cherenkov Effect



$$\boxed{\cos\theta = \frac{1}{\beta n(\lambda)}}$$

Adapted from http://www.gae.ucm.es/~emma/tesina/img10.png

Cherenkov PID

- Threshold detector
  - Cherenkov light is a signal that the particle's speed exceeded *c/n.* For a given momentum, this implies the mass is below some corresponding threshold value.
  - Combinations of detectors with different *n* values can establish that the mass of particle is between certain bounds.
- Differential detector
  - By measuring the emission angle of the light, the particle velocity can be determined.
- RICH
  - A ring imaging Cherenkov detector (RICH) incorporates position sensitive detectors transverse to the particle momentum direction. The resulting Cherenkov light appears as a ring on the detector.
  - For a fixed, thin radiator, the ring diameter is a measure of the particle velocity.

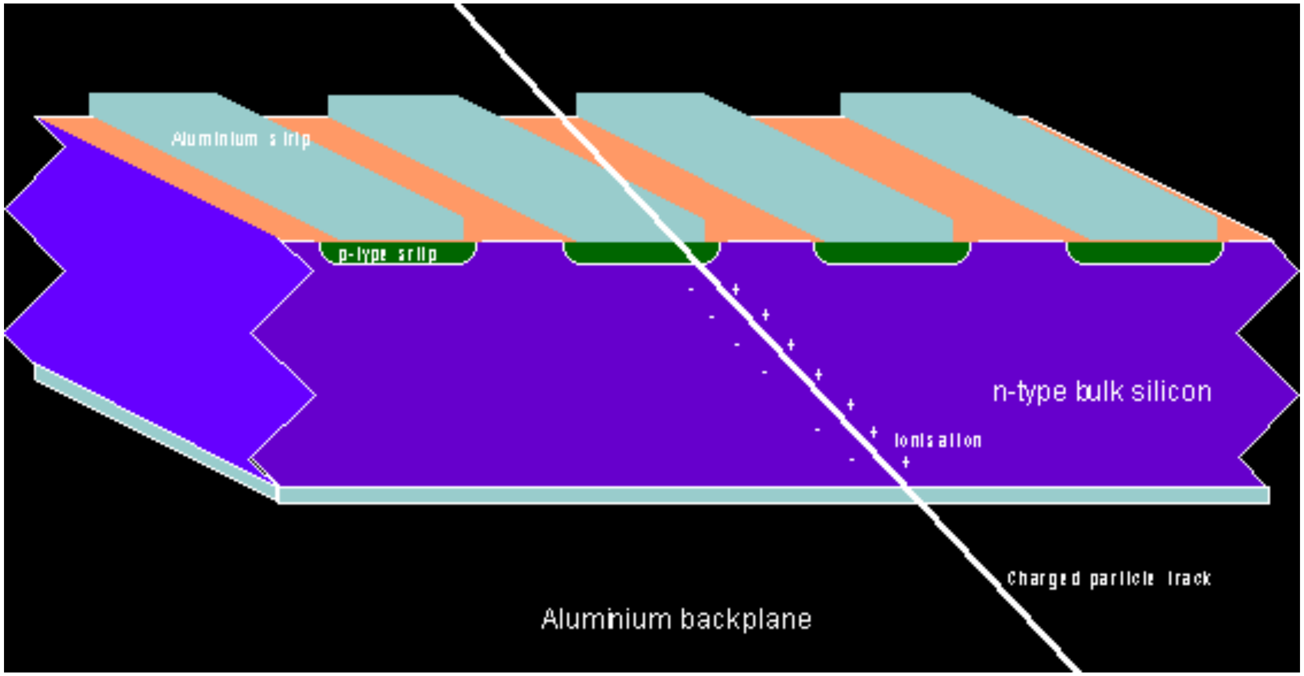
Semiconductor Detectors

- Si and Ge semiconductor detectors register currents generated from creation of electron-hole pairs.
- Creation of an electron-hole pair requires only a few eV of energy deposition.
  - Wafers can be made very thin and still give detectable signals: minimizes multiple scattering and energy straggling, etc.
  - Suitable for very low energy as well as minimum ionizing particles.
- Reverse bias electric field:
  - Prevents electrons and holes from recombining.
  - Allows collection of charge at a set of electrodes.

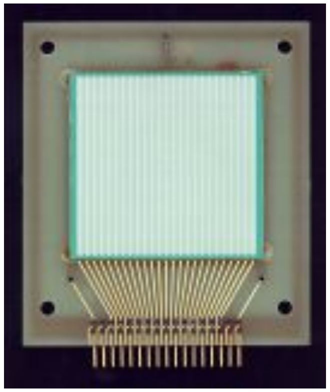
Semiconductor Detectors, cont'd.

- Higher density than gaseous ionization detectors
  - Greater stopping power
  - Better energy resolution
- Very compact
  - Position resolutions of several μm.
  - Can be placed close to interaction region, minimizing size and cost.
- Fast response times
  - Suitable for high rate environments

Silicon Strip Detectors



From http://hepwww.rl.ac.uk/OpenDays98/Detectors/SCT/board1f_inv2.gif



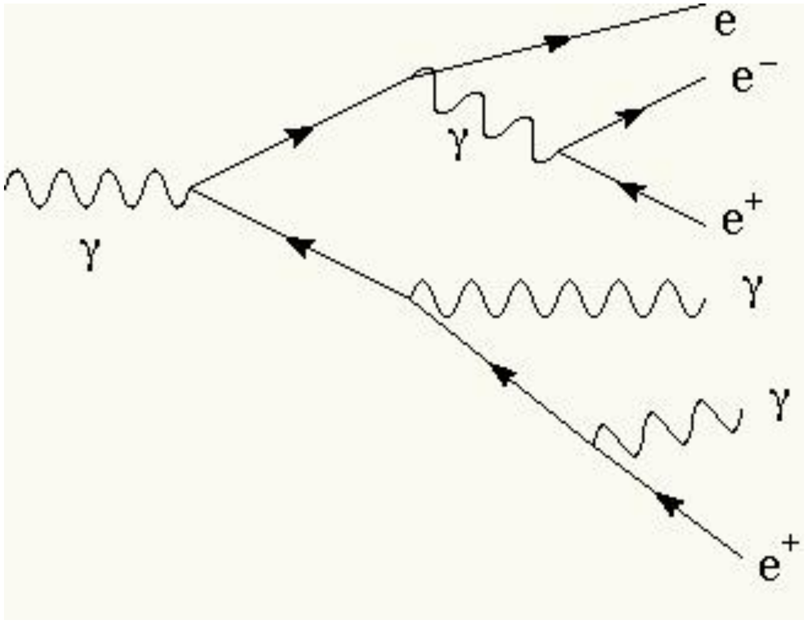
From http://www.ph.ed.ac.uk/nuclear/vlsi/strip134x160.jpeg

Calorimeters

- In certain applications momentum measurements using magnetic fields and position sensitive detectors are impractical or too expensive.
- Even with measurement of momentum, an independent measurement of energy can provide particle ID.
- Calorimeters measure the total amount of energy of a particle by essentially stopping all the secondary particles created during interactions in the calorimeter material.

Electromagnetic Shower

- A high energy photon or electron deposits its energy in an ever-expanding shower: *e*$^+$/*e*$^-$ pair production and bremmstrahlung radiation, …



From: http://en.wikipedia.org/wiki/Image:Shower.jpg

Energy resolution governed by statistical fluctuations:

$$\frac{\Delta E}{E} = \frac{C}{\sqrt{E\,(\mathrm{GeV})}}, \qquad C \sim 0.2$$

Sampling Calorimeters

- **Sampling calorimeters** include passive absorber material (for example lead) interspersed with active sampling devices, which allow collection of the produced charge or photons.
- They measure the development of the *shower* as the particle traverses the detector.
- Advantages
  - Less expensive (lead is relatively cheap).
  - More compact since absorber can be very dense.
- Disadvantage
  - Energy resolution is degraded, since the sampling fluctuations are larger.

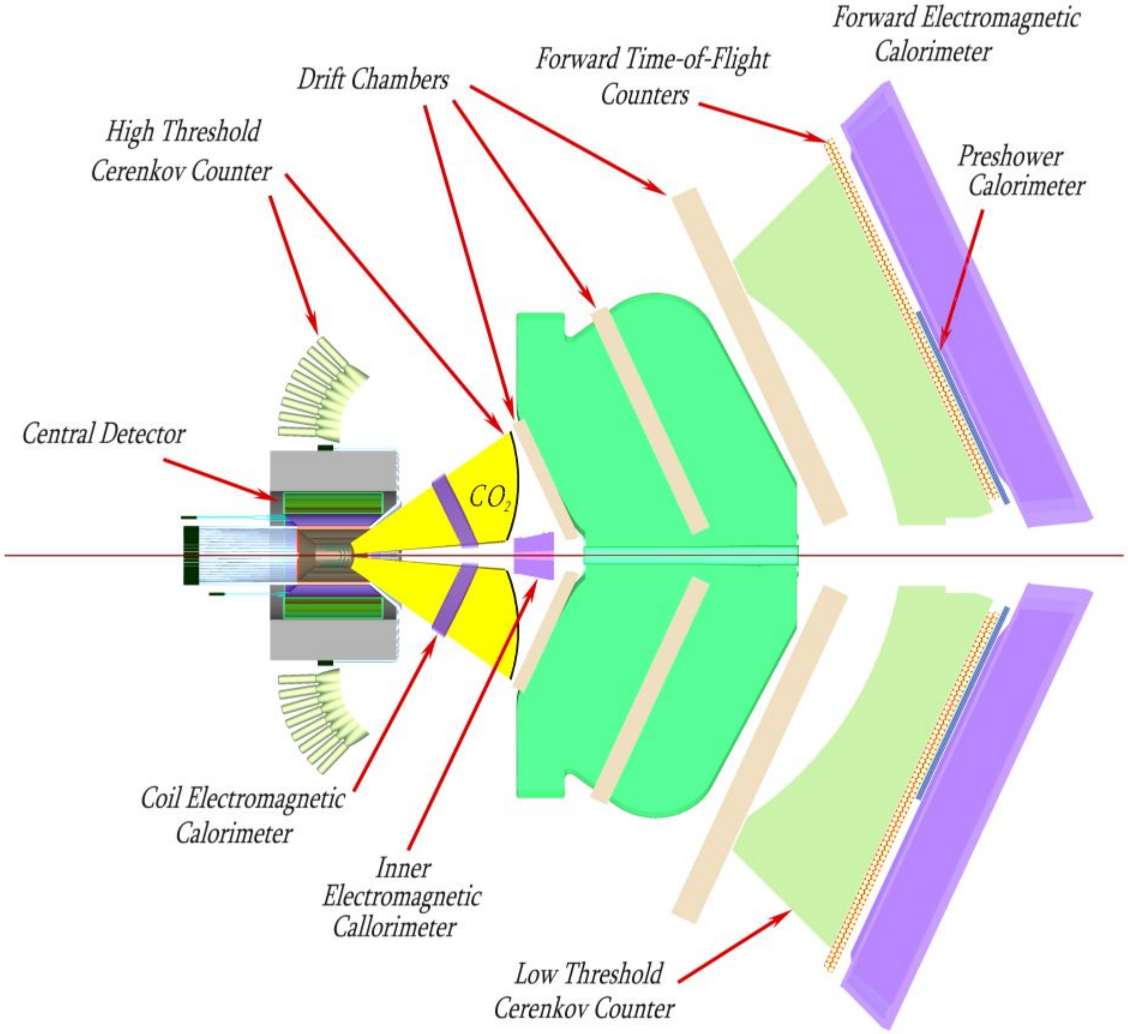
Hadronic vs. Electromagnetic Calorimeters

- Massive particles do not radiate appreciably and so deposit their energy mostly via nuclear collisions.
- The resulting **hadronic shower** requires a much thicker detector to fully contain it.
- For certain detector thickness one can use this to discriminate between hadrons and electrons, since only the latter will deposit all of their energy.
- Hadronic showers have greater inherent fluctuations than EM showers.
  - Any produced neutrinos escape without energy deposition.
  - Neutral pions decay into two photons which induce their own showers and deposit energy locally: influenced by detector inhomogeneity, such as in sampling calorimeters.

Layered Detection

- High energy nuclear and particle physics facilities incorporate combinations of detectors.
  - Triggering detectors inform data acquisition system that there was a particle: scintillators and/or Cherenkov detectors, …
  - Tracking detectors
  - Particle ID: calorimeters, Cherenkov, ToF, …

JLab CLAS Schematic



From http://www.jlab.org/Hall-B/clas12/Photos/CLAS12_2Db.jpg

JLab CLAS

From http://www.cerncourier.com/objects/2002/cernjlab1_5-02.jpg