PHYS 3446 – Lecture #12

Monday, Mar. 7, 2005
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• Particle Detection
  • Ionization detectors
  • MWPC
  • Scintillators
  • Time of Flight Technique
  • Cerenkov detectors
  • Calorimeters
Announcements

• Second term exam
  – Date and time: 1:00 – 2:30pm, Monday, Mar. 21
  – Location: SH125
  – Covers: CH4.5 – CH 8
Particle Detectors

• Subatomic particles cannot be seen by naked eyes but can be detected through their interactions within matter

• What do you think we need to know first to construct a detector?
  – What kind of particles do we want to detect?
    • Charged particles and neutral particles
  – What do we want to measure?
    • Their momenta
    • Trajectories
    • Energies
    • Origin of interaction (interaction vertex)
    • Etc
  – To what precision do we want to measure?

• Depending on the above questions we use different detection techniques
Particle Detection

We know x, y starting momenta is zero, but along the z axis it is not, so many of our measurements are in the xy plane, or transverse.
Ionization Detectors

• Measures the ionization produced when an incident particles traverses through a medium

• Can be used to
  – Trace charged particles through the medium
  – Measure the energy \( \frac{dE}{dx} \) of the incident particle
    • Must prevent re-combination of ion-electron into an atom after the ionization
    • Apply high electric field across medium
      – Separates charges and accelerates electrons
Ionization Detectors – Chamber Structure

• Basic ionization detector consists
  – A chamber with an easily ionizable medium
    • The medium must be chemically stable and should not absorb ionization electrons
    • Should have low ionization potential ($\overline{I}$) ➔ To maximize the amount of ionization produced per given energy
  – A cathode and an anode held at some large potential difference
  – The device is characterized by a capacitance determined by its geometry
Ionization Detectors – Chamber Structure

- The ionization electrons and ions drift to their corresponding electrodes, to anode and cathode
  - Provide small currents that flow through the resistor
  - The current causes voltage drop that can be sensed by the amplifier
  - Amplifier signal can be analyzed to obtain pulse height that is related to the total amount of ionization
Ionization Detectors – HV

- Depending on the magnitude of the electric field across the medium different behaviors are expected
  - Recombination region: Low electric field
  - Ionization region: Medium voltage that prevents recombination
  - Proportional region: Large enough HV to cause acceleration of ionization electrons and additional ionization of atoms
  - Geiger-operating region: Sufficiently high voltage that can cause large avalanche if electron and ion pair production that leads to a discharge
  - Discharge region: HV beyond Geiger operating region, no longer usable
Ionization Counters

- Operate at relatively low voltage
- Generate no amplification of the original signal
- Output pulses for minimum ionizing particle is small
- Insensitive to voltage variation
- Have short recovery time ➔ Used in high interaction rate environment
- Response linear to input signal
- Excellent energy resolution
- Liquid argon ionization chambers used for sampling calorimeters
- Gaseous ionization chambers are useful for monitoring high level of radiation, such as alpha decay
Proportional Counters

- Gaseous proportional counters operate in high electric fields \( \sim 10^4 \text{ V/cm} \).
- Typical amplification of factors of \( \sim 10^5 \).
- Use thin wires (10 – 50 \( \mu \text{m} \) diameter) as anode electrodes in a cylindrical chamber geometry.
- Multiplication occur near the anode wire where the field is strongest causing secondary ionization.
- Sensitive to the voltage variation not suitable for energy measurement.
- But used for tracking device.
Multi-Wire Proportional Chambers (MWPC)

- G. Charpak et al developed a proportional counter in a multiwire proportional chamber
  - One of the primary position detectors in HEP
- A plane of anode wires positioned precisely with about 2 mm spacing
- Can be sandwiched in similar cathode planes (in <1 cm distance to the anodes) using wires or sheet of aluminum
Multi-Wire Proportional Chambers (MWPC)

- These structures can be enclosed to form one plane of the detector
- Multiple layers can be placed in a succession to provide three dimensional position information
Momentum Measurements

- A set of MWPC planes placed before and after a magnetic field can be used to obtain the deflection angle which in turn provide momentum of the particle.

\[
p = \frac{RBze}{c}
\]
\[
L = R \sin \theta
\]

- Multiple relatively constant electric field can be placed in each cell in a direction transverse to normal incident Drift chambers.

- Typical position resolution of proportional chambers are on the order of 200 \( \mu \text{m} \).
A Schematics of a Drift Chamber

Primary Ionization created
Electrons and ions drift apart

Secondary avalanche occurs
Geiger-Muller Counters

- Ionization detector that operates in the Geiger range of voltages
- For example, an electron with 0.5MeV KE that loses all its energy in the counter
- Assume that the gaseous medium is helium with an ionization energy of 42eV.
- Number of ionization electron-ion pair in the gas is
  \[ n = \frac{0.5 \times 10^6 \text{eV}}{42 \text{eV}} \approx 12,000 \]
- If the detector operates as an ionization chamber and has a capacitance of 1 nF, the resulting voltage signal is
  \[ V = \frac{Q}{C} = \frac{ne}{C} = \frac{1.2 \times 10^4 \times 1.6 \times 10^{-19} C}{1 \times 10^{-9} F} \approx 2 \times 10^{-6} V \]
- In Geiger range, the expected number of electron-ion pair is of the order \(10^{10}\) independent of the incoming energy, giving about 1.6V pulse height
(Dis) Advantage of Geiger-Muller Counters

- Simple construction
- Insensivity to voltage fluctuation
- Used in detecting radiation

Disadvantages

- Insensitive to the types of radiation
- Due to large avalanche, takes long time (~1ms) to recover
  - Cannot be used in high rate environment
Scintillation Counters

• Ionization produced by charged particles can excite atoms and molecules in the medium to higher energy levels

• The subsequent de-excitation process produces lights that can be detected and provide evidence for the traversal of the charged particles

• Scintillators are the materials that can produce lights in visible part of the spectrum
Scintillation Counters

• Two types of scintillators
  – Organic or plastic
    • Tend to emit ultra-violate
    • Wavelength shifters are needed to reduce attenuation
    • Faster decay time \(10^{-8}\)s
    • More appropriate for high flux environment
  – Inorganic or crystalline (NaI or CsI)
    • Doped with activators that can be excited by electron-hole pairs produced by charged particles in the crystal lattice
    • These dopants can then be deexcited through photon emission
    • Decay time of order \(10^{-6}\)sec
    • Used in low energy detection
Scintillation Counters – Photo-multiplier Tube

• The light produced by scintillators are usually too weak to see
  – Photon signal needs amplification through photomultiplier tubes

  • Gets the light from scintillator directly or through light guide
    – Photocathode: Made of material in which valence electrons are loosely bound and are easy to cause photo-electric effect (2 – 12 cm diameter)
    – Series of multiple dynodes that are made of material with relatively low work-function
      » Operating at an increasing potential difference (100 – 200 V difference between dynodes)
Scintillation Counters – Photo-multiplier Tube

- The dynodes accelerate the electrons to the next stage, amplifying the signal to a factor of $10^4 - 10^7$
- Quantum conversion efficiency of photocathode is typically on the order of 0.25
- Output signal is proportional to the amount of the incident light except for the statistical fluctuation
- Takes only a few nano-seconds for signal processing
- Used in as trigger or in an environment that requires fast response
- Scintillator+PMT good detector for charged particles or photons or neutrons
Some PMT’s

The Photomultiplier Tube

- Incident Light
- Semitransparent Photocathode
- Photoelectron Trajectories
- Focusing Electrodes
- Dynodes
- Electron Multiplier
- Anode

Super-Kamiokande detector

Monday, Mar. 7, 2005

PHYS 3446, Spring 2005
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Time of Flight

• Scintillator + PMT can provide time resolution of 0.1 ns.
  – What position resolution does this corresponds to?
    • 3cm

• Array of scintillation counters can be used to measure the time of flight (TOF) of particles and obtain their velocities
  – What can this be used for?
    • Can use this to distinguish particles with about the same momentum but with different mass
  – How?
    • Measure
      – the momentum (p) of a particle in a magnetic field
      – its time of flight (t) for reaching some scintillation counter at a distance L from the point of origin of particle
      – Determine the velocity of the particle and its mass
Time of Flight

- TOF is the distance traveled divided by the speed of the particle, \( t = \frac{L}{v} \).
- Thus \( \Delta t \) in flight time of the two particle with \( m_1 \) and \( m_2 \) is
  \[
  \Delta t = t_2 - t_1 = L \left( \frac{1}{v_2} - \frac{1}{v_1} \right) = \frac{L}{c} \left( \frac{1}{\beta_2} - \frac{1}{\beta_1} \right)
  \]
- For known momentum, \( p \),
  \[
  \Delta t = \frac{L}{c} \left( \frac{E_2}{pc} - \frac{E_1}{pc} \right) = \frac{L}{pc^2} \left[ \sqrt{m_2^2c^4 + p^2c^2} - \sqrt{m_1^2c^4 + p^2c^2} \right]
  \]
- In non-relativistic limit,
  \[
  \Delta t = \frac{L}{p} (m_2 - m_1) = \frac{L}{p} \Delta m
  \]
- Mass resolution of \( \sim 1\% \) is achievable for low energies
Assignments

1. Derive Eq. 7.10
2. Carry out computations for Eq. 7.14 and 7.17
3. Due for these assignments is Wednesday, Mar. 23.