Particle Detection Techniques

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To study the interactions of elementary particles or to try to create (i.e. discover) new particles, we typically bang two particles against each other and see what comes out.

Because of the equivalence of mass and energy, the energy of the colliding particles can be transformed into the mass of other particles.

We expect that anything new that is created will be very short lived. We, therefore, will likely see only the long-lived decay products and not the original new objects.

We also can detect particles coming from space and attempt to infer the reactions that created them.
How Can One Detect Elementary Particles?

- Elementary particles are too small to see with your eyes.
- How can you detect their presence?
  - Develop a scheme by which the particle interacts with matter and leaves a remnant trail.
  - The remnant trail could be a visible trail to be photographed.
  - It could be an electronic signal that can be analyzed by electronics and computers.
- Charged particles moving through matter often interact with atoms creating free electrons and ions, electron-ion pairs.
  - So how can we make use of this?
The Cloud Chamber

- One of the earliest detectors was the Wilson Cloud Chamber.
- One can see the trails of particles passing through the chamber but it’s difficult to do much more than say “Gee wiz!”
- The traversing charged particle creates a trail of electron-ion pairs which form nucleation centers for the gas to condense since the gas is kept just above the condensation temperature.
Bubble Chambers

• The Bubble Chamber was a significant improvement in technology.
• By pulsing the piston, the liquid can be cleared of bubbles (compression) and made ready for new particles (releasing the piston to make the liquid super cool).
• Cameras can photograph the tracks with the shutter synchronized to the piston pulses.
• A beam of particles was typically aimed at the contents of the bubble chamber so the liquid inside served as both target and detector.

Fermilab’s 15 ft Bubble Chamber
What to Do with the Photographs?

• By enclosing the bubble chamber in a magnetic field, the charge particles are bent into circular paths.
  – Positive and negative particles bend in opposite directions.
  – The radius of curvature is proportional to \( p/B \) 
    (\( p = \) momentum, \( B = \) magnetic field strength)
  – One can then determine the charge and momentum of the charged particles.

• By placing three cameras at appropriate angles, one can reconstruct a 3-D view of the event.

• Each photograph must be scanned for something interesting and then each track must be digitized.

• One improvement was to trigger the cameras based upon other information indicating something interesting happened.

• But analysis was still very laborious.
Scintillation Detectors

- Some types of material create light when charged particles pass through them.
  - Instead of ionizing the atoms, the passing charged particle excites the outer atomic electrons to a higher energy state. When the atom returns to its ground state, it emits a photon.
    - It is important that a large number of photons are emitted, i.e. many atoms are excited and then decay.
  - There are inorganic scintillators (e.g. NaI), organic solids (e.g. plastic doped with scintillating material), organic liquids.
- The emitted light is typically collected at a photo-multiplier tube which converts the photons to electrons (photo-cathode) and then amplifies the electron signal to be analyzed by other electronics.
Example of a Photomultiplier Tube

Diagram of a scintillation counter.

Scintillation Detectors Pros & Cons

• **Advantages:**
  – Electrical signal from PMT can be analyzed directly by other electronics and/or fed to a computer.
  – Fast signals (ns rise-times) – good for timing applications (e.g. TOF).
  – Self triggering with discriminator – good for trigger signals.

• **Disadvantages:**
  – Typical large size limits position measurement resolution.
  – Photo-multiplier tubes are expensive.

• **Recent advances:**
  – Scintillating fibers.
  – Solid state photo detectors.
Wire Chambers

- Wire chambers are a class of detectors that use gas for the interacting material and collect the freed electrons and/or ions on a wire.
- The simplest is a Geiger Counter.
  - A large voltage is applied between the cathode shell and the anode wire.
  - The ionized gas typically causes a breakdown (spark) across the poles.
  - Simple electronics counts the number of breakdowns.
Multiwire Chambers

- Multiwire chambers stretch many anode wires in a plane with a cathode plane of wires on both sides forming nearly vertical field lines ending on each anode wire.
  - Windows enclose the gas volume.
  - The voltage (electric field) is chosen such that the ionization path doesn’t cause a breakdown but rather the free electrons are collected on the anode and amplified.
  - An older version (spark chamber) allowed sparks to form.

- Measures the position of the passing particle in one dimension.
  - Multiple rotated planes provide 2-D.
  - Position accuracy limited by wire spacing (typically several millimeters at best).

- Position accuracy can be improved with multiwire drift chambers.

- Timing is a bit slow – 10s to 100s of ns.

- Advanced version using straw tubes.
Silicon Detectors

- A big advance was made with the development of silicon detectors.
- A silicon wafer (~300 µm thick) replaces the gas chamber.
- Strips implanted (doped) in one side of the silicon replace the wires.
- A voltage is applied between the back plane of the wafer and the implanted strips on the other side creating reverse biased diodes.
- The resulting electric field causes ionized free electrons to be collected on one pole and holes to be collected on the other.
- The advances in photolithography developed by the IC industry allows the strips to be fabricated with spacing of 10s of microns.
  - Typical position accuracies are then 10s of microns.
- Pixel detectors cut the strips into many short pieces such that each pixel is of order 200 µm x 50 µm giving an immediate 2-D measurement.
Features:
- 4 single-sided sensors at 40 mrad crossing angle
- 1536 strips with 80 \( \mu \)m pitch
- Multi-Chip Unit
- Large dimensions (12 cm x 6 cm x 1.1 mm)
A Sector of One ATLAS Strip Detector Barrel

System Test with 15 modules mounted on a barrel sector at CERN.
Inner Most Barrel Complete at Oxford

As it looked waiting for shipment from Oxford to CERN
384 modules mounted

ATLAS contains 4088 modules, which equates to 6.3 million channels.
What Can We Measure for Each Particle?

• All of these detectors detect the position of charged particles as they fly by.
  – Fly out from a collision of particles
  – Possibly fly in from out space

• As we saw with bubble chambers, placing the detectors inside a magnetic field allows the measurement of the charge and momentum of each charged particle.

• Can we learn anything else about the particles?
  – Can we determine what type of particle they are?
What about Neutral Particles?

• Neutral particles do not as readily interact with matter as do charged particles.
  – Low energy photons can be captured in some material by the photo-electric effect or Compton scattering such that a signal can be detected.
  – Likewise slow neutrons can be stopped by nuclear capture making an unstable nucleus or by nuclear collisions.
  – These are small signals and high energy neutrals typically pass through most material that are capable of creating a detectable signal.

• The typical method to detect high energy neutrals is to force them to interact in dense material (e.g. lead or iron) thus creating a large splash of other particles, many charged, and then to detect the charged products.
Calorimeters

- Neutral particles don’t interact with a magnetic field. We need to measure their energy by absorbing all their energy and measuring the energy deposited – a calorimeter.

- Some calorimeters are segmented such that the direction of the deposited energy can be measured thus giving a trajectory of the incoming neutral.

- If we place the tracking detector in front of the calorimeter, then the absence of a charged track pointing to the deposited energy in the calorimeter implies the energy came from a neutral.
Particle ID

- Particle ID is often the most difficult task – many schemes measure velocity in addition to momentum.

- Time of Flight (TOF):
  - TOF + distance => velocity; combined with momentum => mass
  - This will often isolate the ID of charged particles.
  - At LHC energies & ATLAS sizes, TOF differences are too small.

- Cherenkov Radiation Detector:
  - The angle of the radiation cone is dependent upon particle velocity.
  - Measuring this angle is often difficult in a multi-particle detector.

- Transition Radiation Detector:
  - The energy of emitted photons by a charged particle transitioning a change of media is again dependent upon its velocity.

- Often ID is accomplished by a process of elimination, for example:
  - e\(^-\), e\(^+\) and γ produce a characteristic shower in a segmented calorimeter.
  - Knowledge of a track or missing track plus this shower makes this ID.
  - Muons can be identified by detecting tracks after sufficient material to stop all other particles (except neutrinos which are normally not detected at all).
The ATLAS Detector

The ATLAS Detector makes use of many of the technologies we just discussed.