Particle Detectors

How to See the Invisible
Which Subatomic Particles are Seen?

Which particles live long enough to be visible in a detector?
Which Subatomic Particles are Seen?

Which particles live long enough to be visible in a detector?

- Protons
- Electrons
- Photons
- Neutrons
Which Subatomic Particles are Seen?

Which particles live long enough to be visible in a detector?

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<th>Protons</th>
<th>Anti-protons</th>
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A few special cases of strange baryons.
How are Subatomic Particles Seen?
How are Subatomic Particles Seen?

By their interactions with ordinary matter. There's a finite number of possible interactions:

- Ionization of atoms
- Scintillation
- Cherenkov radiation
- Transition radiation
- Synchrotron radiation
- Interaction with nucleus
- Bremstrahlung
- Photoelectric effect
- Compton scattering
- Pair production

Ultimately, detection requires creating an electrical signal.
Detecting Photons

Let's start with processes important for the detection of photons.

- Photoelectric effect
- Compton scattering
- Pair production
The Photoelectric Effect

Familiar from Modern Physics course. Einstein’s explanation requires quantized energy of photons.

Energy of liberated electrons depends on the frequency of light (photons).

Rate of electrons (current) depends on the intensity of the light (rate of incident photons).

Photomultiplier tubes use the photoelectric effect to convert incoming photons to electrons (single photon detection).
Compton Scattering

A second type of photon-matter interaction. Usually appears when discussing relativity.

Important for intermediate energy photons.

Incident photon loses energy when ejecting an electron from an atom.

Process is important to “break down” a high energy photon into electrons. The energy of the photon determines the final number of electrons produced. (Calorimetry)
Pair Production

A third type of photon-matter interaction. Example of conversion of energy into mass.

Important for high energy photons.

Incident photon converts into an electron-positron pair.

Presence of matter is required to conserve energy-momentum.

Process is important to “break down” a high energy photon into electrons. The energy of the photon determines the final number of electrons produced. (Calorimetry)
Detecting Electrons

Three processes are unique to electrons.*

Bremstrahlung

Transition radiation

Synchrotron radiation

* Almost always true. Ask if you want to hear about an exception.
Bremstrahlung

A German word for “braking radiation”.

Important for high energy electrons.

Incident electron emits a photon (usually x-ray), when accelerated in the electric field of a nucleus.

Process is important to “break down” a high energy electron into low energy electrons. The energy of the incident electron determines the final number of electrons produced. (Calorimetry)
Synchrotron Radiation

Like Bremstrahlung, but acceleration due to a magnetic field.
Transition Radiation

Radiation produced when a highly relativistic electron passes through materials with different indices of refraction.
Detecting Charged Particles

The remaining processes apply to all charged particles and are therefore widely applicable.

- Ionization of atoms
- Interaction with nucleus
- Scintillation
- Cherenkov radiation
Ionization of atoms may be the single most important process for particle experiments.

Primary process for “tracking” particles

Also important for producing large numbers of electrons for a detectable current.
Energy Loss

\[ \mu^+ \text{ on Cu} \]

Lindhard-Scharff

Andersen-Ziegler

Nuclear losses

\[ \mu^- \]

Bethe-Bloch

Minimum ionization

Radiative effects reach 1%

\[ E_{\mu e} \]

Radiative losses

Without \( \delta \)

Stopping power [MeV cm\(^2\)/g]

[MeV/c] [GeV/c] [TeV/c]

\( \beta_\gamma \)

Muon momentum

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Dependence on Material

- Energy loss depends on the type of material and particle.
- Atoms with more higher $Z$ have less energy loss per g/cm$^2$
- But their higher density (g/cm$^3$) more than makes up for this.
Cerenkov Radiation

- Emitted when a particle exceeds the speed of light in a medium
- Like the shock wave from a supersonic plane
- Cone angle is related to particle velocity
Scintillation

- Many materials emit light when atoms or molecules are excited by a charged particle passing nearby.
- Emitted light is called scintillation.
- Scintillating medium usually transparent.
- Light (single or few photons) detected by a photomultiplier.
Nuclear Interactions

Primarily important for hadrons: protons, neutrons, pions, and kaons.

Nuclear Interaction of a Galactic Cosmic Ray and a Nucleus in a Rock

\[
p + \text{Si}^{28} \rightarrow \text{Ne}^{21} + \text{He}^{4} + 3p + n
\]
Building an Experiment

Ideally we want to identify everything (particle type, charge, spin, point of origin, momentum at point of origin) emerging from a collision in order to reconstruct exactly what occurred.

Interesting collisions contain short lived particles (top, bottom, or charm quarks, W or Z bosons, Higgs particles, or a deconfined quark state) that can’t be directly seen, and must be inferred from the products they leave behind.

We build a detector that comes as close to achieving this goal as reasonable.
Collide
Particles
At very high energies and convert energy into mass (i.e. other particles)
A General Purpose Detector