Particle Detection
How to see the invisible

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What Is Detection?

• How can we “see” a subatomic particle?
  o By its interactions with ordinary matter.

• What kind of interactions does a subatomic particle have with ordinary matter?
  o Ordinary matter is composed of atoms. Interactions can occur with the:
    • bulk material,
    • molecular bonds,
    • atomic electrons, and
    • nuclei.
  o The atomic picture is very useful!
A General Purpose Detector
Detection

• Requires creating a measurable signal:
  o something that can be seen by eye
  o an electric signal that can be registered
  o a chemical change to something that can be made visible after a chemical reaction

• We normally consider the detector material to be at rest
  o incident particle on fixed target geometry
Where to Begin?

• There are hundreds of particles:
  o leptons, quarks
  o bosons: $\gamma$, $W$, $Z$, $H$
  o combinations of quarks: mesons and baryons
  o deuterons, alphas, ...
  o new particles: axions, SUSY, dark matter, ...

• Can we winnow this list down?

• So many possible detector materials:
  o gas, liquid, solid
  o atomic or molecular
  o H to U

• And so many possible signals:
  o heat, light, electric

• Can we simplify this?
Which Particles?

• Which particles are directly detectable?
  o Those that live long enough to traverse detector material

• Enumerate them (it’s a small number):
  o photon $\gamma$
  o electron and positron $e^\pm$
  o muon and anti-muon $\mu^\pm$
  o charged pions $\pi^\pm$
  o charged kaons $K^\pm$
  o proton and anti-proton $p^\pm$
  o neutrons $n$ and anti-neutrons $\bar{n}$, and neutral kaon $K^0$
  o a few of the strange baryons, in special cases
  o some speculative particles like dark matter or mag. monopoles
What About Other Particles?

- Detection of all other particles is via their decay products, for example:
  - $K^0_S \rightarrow \pi^+\pi^-$
  - $D^+(s) \rightarrow \phi \pi^+ \rightarrow K^+K^-\pi^+$ (see plot)
  - $Z^0 \rightarrow e^+e^-, \mu^+\mu^-$, $b\bar{b}$
    - $b$ quarks are seen as jets with a displaced vertex
    - jets are a collection of detectable particles in a narrow cone
  - $W^\pm \rightarrow e^\pm\nu_e, \mu^\pm\nu_\mu$
    - neutrinos aren’t seen so much as inferred from an imbalance of momentum perpendicular to the collision axis referred to as missing transverse energy or MET.
What Can Be Measured?

• First is to detect that a particle is present.
  o For low energy photons, dark matter, and [low energy] neutrinos, that is about all that can be measured

• For other particles we would like to know:
  o charge
  o type of particle (mass)
  o energy and momentum
  o spin(?!)

• These are determined from the way particles interact with a macroscopic detector (matter).
The Interactions

• The basic interactions can be further subdivided into a surprisingly short list.

• I will not discuss interactions that effect molecular bonds.
  - These are not used in electronic detectors since chemical processing is needed (up to now).
  - These come into play with photographic emulsions and some types of plastic detectors.
  - Other famous example: Ray Davis’ solar neutrino expt.
  - Consult references if you need more information.
1. Interactions with (or requiring) atomic nuclei --- may be familiar from modern physics courses:

a) Pair production
b) Bremstrahlung
c) Nuclear (hadronic) interaction

- The first applies to photons, the second to electrons (mostly), and the last to hadrons.
Interactions (cont’d)

2. Interactions with atomic electrons are widely used:
   a) Compton Scattering
   b) Photoelectric effect
   c) Ionization of atoms
   d) Excitation of atoms

• The first two apply only to photons, the last two apply to all particles.
Interactions (cont’d)

3. Interactions with bulk material may be the least familiar:
   a) Cerenkov radiation
   b) Transition radiation

• I will not be able to cover these today.
  o Check the backup slides for some information on these.
  o A good introduction can be found in Jackson’s *Classical Electrodynamics*. 
The Physics of Detection
Interactions with Electrons

- Interactions with atomic electrons may be the single most important detection process for particle experiments.
  - Primary process for “tracking” particles
  - Also important for producing large numbers of free electrons for a detectable current.
The Photoelectric Effect

Familiar from Modern Physics class. Einstein’s explanation requires quantized energy for 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). Silicon detectors (strips, pixels, CCD’s) use the photoelectric effect to create an electron-hole pair.
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. (See calorimetry)
The Bethe-Bloch Formula

- Semi-classical calculation of energy loss

\[-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \left( \frac{2mec^2 \beta^2 \gamma^2 T_{\text{max}}}{I^2} \right) - \beta^2 - \frac{\delta}{2} \right]\]

- Note the competition between $\ln(\beta^2 \gamma^2)$ and $-\beta^2$
  - Causes a minimum in the energy loss
  - Minimum energy loss scales roughly as $Z/A$ of the material.
    - 4 MeV cm$^2$/g for H to about 1 MeV cm$^2$/g for heavy elements
  - Minimum energy loss when $\beta \gamma \approx 3$ to 3.5
  - Depends on kinematics, independent of particle type

- $\delta$ term represents density effect
Energy Loss

Stopping power [MeV cm^2/g]

- Nuclear losses
- Anderson-Ziegler
- Lindhard-Scharff

\( \mu^+ \) on Cu

Bethe-Bloch

Radiative losses

Minimum ionization
Radiative effects reach 1%

\( E_{\mu c} \)

\( \beta_\gamma \)

[MeV/c]

[GeV/c]

[TeV/c]

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Dependence on Material

- Energy loss depends on the type of material and particle.
- Atoms with higher Z have less energy loss per g/cm²
- But their higher density (g/cm³) more than makes up for this.
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 (one to a few photons) detected by a photomultiplier.
Interactions with Nuclei

• Two types of interaction are possible
  o Electromagnetic
  o Strong

• Details are in the backup slides
(1) Electromagnetic

- Mostly single photon exchange
  - elastic interactions
- When a light object (particle) scatters elastically from a heavy object (nucleus):
  - little loss of energy
  - can change direction significantly
    - think of the Rutherford scattering experiment
    - most scattering is small angle
    - large number of small angle scatters can be treated statistically
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. (See calorimetry.)
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. (See calorimetry.)
Synchrotron Radiation

Like Bremstrahlung, but acceleration due to a magnetic field.
(2) Strong Interactions

Important for measuring the energy of protons, neutrons, pions, and kaons (calorimetry).
A Typical Detector
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 cannot 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 money allows.
Collide Particles

- at very high energies and convert energy into mass (i.e. other particles)
Collider detectors have converged on a standard configuration. Moving outward from the collision we have:

- precision tracking
- tracking to measure curvature in a solenoidal magnetic field
- Cerenkov detector, TOF, transition radiation det. (optional)
- electromagnetic calorimeter
- hadronic calorimeter
- muon detector (always outermost)
A General Purpose Detector
Tracking

• measure the origin (vertex) of charged tracks
• measure the momentum of charged tracks
• requires:
  o a magnetic field of sufficient strength and extent (to measure radius of curvature)
  o large volume tracking (driven by cost)
  o high precision measurements near the collision pt.
  o possibly some particle ID (dE/dx, TOF, Cerenkov, TRD)
Measuring Momentum

• In a uniform magnetic field
  o $p \cos \theta = 0.3 \ z \ B \ R$
  o where $B$ is in Tesla, $R$ in meters, $z$ in multiples of the proton charge, $p$ in GeV/c.

• The uncertainty on $p$ comes from 2 sources:
  i. resolution of track position measurements
  ii. multiple scattering of material in the detector
  o The second source leads us to use thin silicon detectors or gaseous detectors
Calorimetry

- Measure the energy in charged and neutral particles
- Hadrons interact differently from photons and electrons. EM calorimeter placed before hadronic calorimeter
Measuring Energy

• Convert the energy of high energy particles into $n$ low energy particles
  
  $n \sim E/E_0$ where $E_0$ is the average energy to produce a low energy particle.

  The number of particles is stochastic quantity with Poisson fluctuations $\Rightarrow$ we will measure $n \pm \sqrt{n}$ particles

  The measured energy is $E \pm \sqrt{E}$, so the relative measurement uncertainty is $1/\sqrt{E}$
Photon Detection

• Detecting photons is important in many situations: astronomy, calorimetry, TOF, ...

• Common detectors are
  o photomultipliers
    • fast signals, high sensitivity, low granularity
  o CCDs
    • high granularity, time integrating
CCD

- The sensors for digital cameras
- Semiconductor devices, usually silicon
- Can be customized for sensitivity in IR, visible, or UV.
Muon Detector

• Muons are 200 times heavier than electrons.
• Muons bremstrahl with $(200)^2$ smaller probability
• The result is that they can pass through much more material without interacting than other charged particles.
• Muon detector is basically a charged particle tracker located behind lots of material.
CMS Detector

- **Pixels Tracker**
- **ECAL**
- **HCAL**
- **Solenoid**
- **Steel Yoke**
- **Muons**

- **Silicon Tracker**
  - Pixels (100 x 150 μm²)
  - ~1m²: 66M channels
  - Microstrips (50-100μm)
  - ~210m²: 9.6M channels

- **Crystal Electromagnetic Calorimeter (ECAL)**
  - 76k scintillating PbWO₄ crystals

- **Preshower**
  - Silicon strips
  - ~16m²: 137k channels

- **Steel Return Yoke**
  - ~13000 tonnes

- **Superconducting Solenoid**
  - Niobium-titanium coil carrying ~18000 A

- **Hadron Calorimeter (HCAL)**
  - Brass + plastic scintillator

- **Forward Calorimeter**
  - Steel + quartz fibres

- **Muon Chambers**
  - Barrel: 250 Drift Tube & 500 Resistive Plate Chambers
  - Endcaps: 450 Cathode Strip & 400 Resistive Plate Chambers

**Specifications**

- **Total weight**: 14000 tonnes
- **Overall diameter**: 15.0 m
- **Overall length**: 28.7 m
- **Magnetic field**: 3.8 T
Backup
(1) Electromagnetic (cont’d)

- Multiple Coulomb scattering (MCS)
  - yields a roughly Gaussian distribution of scattering angles

\[
\mathcal{P}(\theta) d\theta = \frac{1}{\sqrt{2\pi}\theta_0} e^{\theta^2/2\theta_0^2} d\theta
\]

\[
\theta_0 = \frac{13.6\text{MeV}}{\beta \rho c} z \sqrt{x} \left[ 1 + 0.038 \ln \left( \frac{x}{X_0} \right) \right]
\]

- \(X_0\) is called the radiation length of the material
  - characterizes electromagnetic interactions with nuclei in a material

- Scattering independent of particle type (except \(e^-\))
Transition Radiation

Radiation produced when a highly relativistic electron passes through materials with different indices of refraction.
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*
Electromagnetic Showers

• To measure the energy of an incoming particle
  o Convert a single high-energy particle into many low-energy particles, and count the number of particles.
  o The conversion is called a shower.
  o pair production: 1 photon $\rightarrow$ 2 electrons
  o Compton scattering: 1 photon $\rightarrow$ 1 photon + 1 electron
  o bremsstrahlung: 1 electron $\rightarrow$ 1 electron + 1 photon

• After traversing distance $X$ of a medium, the average energy of an electron/photon is:

\[ \langle E \rangle = E_0 e^{-X/X_0} \]
Hadronic Showers

• Same idea as for electromagnetic showers
  
  o incoming particle is a hadron
  o interactions with material characterized by interaction length $\lambda_i$
  o radiation lengths << interaction lengths
  o therefore, electromagnetic calorimeters precede hadronic calorimeters in a detector