Outline

Accelerators
- Linear Accelerators
- Cyclotrons and Synchrotrons
- Storage Rings and Colliders
- Particle Physics Laboratories

Interactions of Particles with Matter
- Charged Particles
- Neutral Particles, Photons

Detectors in Particle Physics
- Position sensitive devices
- Calorimeters
- Particle Identification

Experiments
- Mainly at colliders
### Accelerator Principle

Charged particles are accelerated to high energies using electromagnetic fields $e^-, e^+, p, \text{anti-}p, \text{ionised nuclei, muons}$

### Why are Accelerators used?

Higher energies or momenta allow to probe shorter distances
de Broglie wavelength

$$\lambda = \frac{hc}{pc} = \frac{197 \text{ MeV} \cdot \text{fm}}{p [\text{GeV/c}]}$$

e.g. 20 GeV/c probes 0.010 fm

### Cockroft-Walton Accelerator

High DC voltage accelerates particles through steps created by a voltage divider
Limited to $\sim 1 \text{ MV}$

### Fermilab Injector

Ionised hydrogen, $H_2^-$ source accelerated to 750 kV

### Van de Graaff Accelerator

charge transported by belt
Limited to $\sim 10 \text{ MV}$
**Linear Accelerators - Linac**

**Working Principle - Linac**

Charged particles in vacuum tubes accelerated by Radio Frequency (RF) waves

RF tubes increase in length size as particle speed increases (protons, for e- \( v \approx c \))

**Radio Frequency Acceleration**

Radio Frequency fields \( O(\text{few } 100 \ \text{MHz}) \)
Field strengths – few MV/m - klystrons transported by RF cavities
Oscillating RF polarities produce successive accelerating kicks to charged particles when RF is decelerating particles shielded in RF tubes
Particles in phase with RF

**Fermilab Injector**

400 MeV protons, 150 m long

**Stanford Linear Accelerator (SLAC)**

Largest Linac - 3 km long, 50 GeV e- and e+
Circular Accelerators

**Cyclotron**

Charged particles are deflected in magnetic field $B$ by Lorentz Force $\vec{F}_L = e\vec{v} \wedge \vec{B}$

$\vec{p}[\text{GeV/c}] = 0.3 B[T] \rho[m]$  

radius of curvature $\rho$

Particle accelerated by RF in magnet with $E$ perp. $B$

Protons, limited to $\sim 10$ MeV relativistic effects

**Synchrotron**

B-field and RF synchronised with particle speed  
radius $\rho$ stays constant  
Superconducting dipole magnets  
B-fields up to 8 Tesla  
Quadrupole magnets focus beam  
alternate focusing and defocusir in horizontal and vertical plane

**SpS at CERN**

**Synchrotron Radiation**

Accelerated particles radiate

Energy loss per turn  
most important for $e-$

$$\Delta E = \frac{4\pi e^2 \beta^3 \gamma^4}{3} \frac{1}{\rho}$$
Storage Ring - Colliders

Beams from synchrotron or linac have bunch structure

Secondary Beams
Accelerated beam from synchrotron or linac on target → e, µ, π, p, K, n, ν, Z\textsuperscript{A}X beams
Many different types of experiments

Storage Rings
Particle beams accelerated in synchrotron and stored for extended periods of time

Colliders
Two counter-rotating beams collide at several interaction points around a ring

Luminosity
\[ L = \frac{N_1 N_2}{r_x r_y} f n_B \]

Fermilab
Chicago, [http://www.fnal.gov](http://www.fnal.gov)

Tevatron
Current highest E\textsubscript{CoM} energy collider
1 TeV p on 1 TeV anti-p
maximum 10^{12} anti-p
CERN


PS -- 29 GeV, injector for SPS

SPS -- 450 GeV p onto 450 GeV anti-p
    injector for LEP/LHC

LEP -- 100 GeV e- onto 100 GeV e+

LHC -- will start in 2007
7 TeV p onto 7 TeV p
4 experiments
ATLAS, CMS, LHCb, Alice
Particle Physics Laboratories

CERN, Fermilab
See previous slides

SLAC
California, http://www.slac.stanford.edu
SLC -- 50 GeV e- onto 50 GeV e+
PEP-II -- 9.0 GeV e- onto 3.1 GeV e+
B-factory

DESY
HERA -- 920 GeV p onto 30 GeV e-

KEK
Japan, http://www.kek.jp
KEKB -- 8.0 GeV e- onto 3.5 GeV e+
B-factory
JPARC -- 50 GeV synchroton (in construction)

Cornell
CESR -- 3...6 GeV e- onto 3...6 GeV e+
**Basic Principles**
Mainly electromagnetic interactions, ionization and excitation of matter
“Applied QED”, lots of other interesting physics

**Charged Particles**
Electrons, positrons
Heavier particles: $\mu$, $\pi$, K, p, ...
- **Energy loss**
  - Inelastic collisions with the atomic electrons
- **Deflection**
  - Elastic scattering from nuclei
- **Bremsstrahlung**
- **Photon emission** (Scintillation, Cherenkov)

**Neutral Particles**
Photons
- **Photo electric effect**
- **Compton scattering**
- **Pair Production**

Neutrons, Neutral hadrons
- **Nuclear reactions**

**Neutrinos**
- **Weak reactions**
Energy Loss

**Coulomb Scattering**
Traversing charged particle
scatters off atomic electrons
of medium, causes ionisation

**Energy loss of charged particles**
by ionisation

\[
\langle \frac{dE}{dx} \rangle = -4\pi N_A r_e^2 m_e c^2 Z^2 \frac{1}{A^2} \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\text{max}}}{I^2} - \beta^2 - \frac{\delta^2}{2} \right]
\]

- \( N_0 \) - Avogadro’s number
- \( Z, A \) - atomic and mass number of medium
- \( x \) - path length in medium in g/cm²
- \( x = \rho t \) - mass density \( \rho \) and thickness \( t \) in cm
- \( dE/dx \) measured in [MeV g⁻¹ cm²]
- \( \alpha \) - fine structure constant
- \( r_e = e^2/4\pi\varepsilon_0 m_e c^2 = 2.82 \text{ fm} \) (classical e radius)
- \( \beta, \gamma \) - speed and Lorentz boost of charged particle
- Maximum energy transfer \( T_{\text{max}} \)
- Mean excitation energy \( I \)

\[
T_{\text{max}} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e / M + (m_e / M)^2} \quad I \approx I_0 Z \quad \text{with} \quad I_0 = 10 \text{ eV}
\]

Valid for “heavy” particles \((m \geq m_\mu)\)

- e⁻ and e⁺ \((m_{\text{proj}} = m_{\text{target}}) \rightarrow \) Bremsstrahlung
- \( dE/dx \sim 1/m_{\text{target}} \rightarrow \) scattering off nuclei very small
\[ \langle \frac{dE}{dx} \rangle = -4\pi N A r_e^2 m_e c^2 z^2 Z \frac{1}{A} \beta^2 \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\text{max}}}{I^2} - \beta^2 - \frac{\delta}{2} \right] \]

dE/dx Energy Dependence

- only on \( \beta \gamma \) independent of \( m_{\text{proj}} \)
- For small \( \beta \), \( \frac{dE}{dx} \propto \frac{1}{\beta^2} \)

Minimum Ionising Particles

- For \( \beta \gamma \approx 4 \) or \( \beta \approx 0.97 \) (MIP)

Relativistic rise

- For \( \beta \gamma \gg 1 \), \( \ln \gamma^2 \) term
- Relativistic expansion of transverse E-field
- larger for gases than dense media

Density effect \( \delta \) term

- Cancels relativistic rise cancelled at very high \( \gamma \)
- polarization of medium screens more distant atoms

\[ \frac{dE}{dx} \text{ rather independent of } Z \text{ except hydrogen} \]

\[ \frac{dE}{dx} \approx 1 \ldots 2 \text{ MeV } g^{-1} \text{ cm}^2 \]
Interaction of Photons

How do Photons interact?

Photons are neutral
Photons can create charged particles
or transfer energy to charged particles

Photoelectric effect
Compton scattering
\( e^+e^- \) Pair Production

in Coulomb field of nucleus
which absorbs recoil, requires \( E_\gamma \geq 2m_e c^2 \)

\[ \gamma + \text{nucleus} \rightarrow e^+ e^- + \text{nucleus} \]

\( \gamma \) energy does not degrade, intensity is attenuated

Absorption of Photons in Matter

\[ I = I_0 \exp(-\mu x) \]

\( \mu = \mu_{\text{photo}} + \mu_{\text{Compton}} + \mu_{\text{pair}} + \ldots \)

\( \mu \): Mass attenuation coefficient
\[ \mu_i = \frac{N_A}{A} \sigma_i \quad [\text{cm}^2 / \text{g}] \]

I: Intensity
x: Target thickness

**Diagram:**

- Carbon (Z = 6)
- \( \sigma_{\text{p.e.}} \) - experimental \( \sigma_{\text{tot}} \)

Cross section versus atomic number and photon energy.

- \( \sigma_{\text{coh}} \)
- \( \sigma_{\text{mcoh}} \)
- \( \kappa_x \)
- \( \kappa_e \)
- \( \sigma_{\text{total}} \)

Photon Energy vs. Cross section for different elements.
Experimental Measurements

Momentum, energy, and mass identification of charged and neutral long-lived particles $e, \mu, \pi, K, p, \gamma, n, \nu$

Hadrons versus Quarks

Experiments/detectors measure hadrons
Theory predicts quark and parton distributions
Hadronisation by Monte Carlo methods
Charged Particle Tracking

**Momentum Measurement**

Charged particle trajectories are curved in magnetic fields
\[ p_\perp [\text{GeV}/c] = 0.3B[T]\rho[\text{m}] \]
measure transverse momentum

**Tracking Detectors** (before 1970)
mostly optical tracking devices - cloud chamber, bubble chamber, spark chamber, emulsions
Slow for data taking (triggering) and analysis

**Geiger-Mueller Counter**

Ionisation in gas
\( O(100 \text{ e- ion-pairs/cm}) \)
Avalanche multiplication near wire with gain up to \( 10^6 \)

**Multi-Wire-Proportional Chamber MWPC**

Many wires in a plane
act as individual counters
Typical dimensions: \( L = 5 \text{ mm} \)
\( d = 1 \text{ mm}, a = 20 \mu\text{m} \)
signal \( \propto \) ionisation
Fast, high rate capability
Spatial resolution limited by wire spacing

*Charpak*  
Inventor of MWPC
Tracking Detectors

Drift Chamber

Measure also drift time
Drift velocities 5 ... 50 mm/µs
Improved spatial resolution
100 ... 200 µm
Fewer wires, less material
Volumes up to 20 m³
Best for e+e- detectors
BaBar experiment (SLAC)
~29000 wires
~7000 signal wires

Silicon Detectors

Metal strips, pads, pixels evaporated on silicon wafer
Semi-conductor device
Reverse bias mode
Typically 50 µm spacing
and 10 µm resolution
CMS experiment (LHC)
250 m² silicon detectors
~ 10 million channels
Calorimeters

Shower Cascades
Electron lose energy by Bremsstrahlung
\[-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} \varepsilon^2 \left( \frac{1}{4\pi\varepsilon_0} \frac{e^2}{mc^2} \right)^2 E \ln \frac{183}{Z^{\frac{1}{3}}} \propto \frac{E}{m^2}\]
High energy e- (e+) or \(\gamma\)
\(\pi, K, p, n, \ldots\) produce hadronic showers

Sampling Calorimeter
Alternate between absorber materials (Fe, Pb, U) and active layers (e.g. plastic scintillators)

Homogeneous Calorimeter
Measures all deposited energy
Examples: scintillating crystals (NaJ, CsI, BGO, \(\ldots\)) or cryogenic liquids (argon, krypton, xenon)

Energy measurement
Better resolution for electromagnetic shower

BaBar experiment
6580 CsI (Tl) crystals
Particle Identification

How do we measure Particle type?

Uniquely identified by its mass $m$
Particles have different interactions

Momentum $p = m\gamma\beta c$ of charged particles measured with tracking detectors

Electrons, Photons

Electromagnetic Calorimeter (crystal)
Comparison with momentum (electron)
Shower shape (electrons, photons)

Charged Particle Identification

Have momentum $p = m\gamma\beta c$ \hspace{1cm} $\gamma^2 = 1/(1-\beta^2)$
Need to measure particle velocity $v = \beta c$
Charged particles radiate Cherenkov photons in medium with speed $v$ larger than $c/n$ (refr. index $n$)

$$\cos \theta_c = \frac{1}{n\beta} \text{ with } n = n(\lambda) \geq 1$$

Cherenkov angle measures $v = \beta c$

Ring Imaging Cherenkov Detector

Muons

Most penetrating particle
little Bremsstrahlung
a few metres of iron and only muons are left