General Information

- **Muon Lifetime Experiment**
  - Still some uncertainty whether the experiment will be repaired in time
  - Instructions/Write-Up posted on course web site

- **Individual Study Projects**
  - Ready to sign up?
  - Other ideas?

- **Today’s Agenda**
  - Cosmic Rays
  - Relativistic Kinematics Primer
  - Radioactive sources
  - Radiation Safety Homework
  - Accelerators
  - Principle components of a detector
Our first detector and some history

Electroscope

- 1895: X-rays (Roentgen)
- 1896: Radioactivity (Becquerel)
- But ionization remained, though to a lesser extent, when the electroscope was inserted in a lead or water cavity
On August 7, 1912, Victor Hess ascended in a balloon to an altitude of about 16,000 ft (without oxygen) carrying three electrosopes.

Nobel Prize in 1936 for the discovery of cosmic rays.
Readings on ionization chamber Victor Hess carried aloft in the Böhmen. Above four kilometers the ionization rose rapidly indicating "that rays of very great penetrating power are entering our atmosphere from above".
Cosmic Rays

- **History**
  - 1912: First discovered
  - 1927: First seen in cloud chambers
  - 1962: First $10^{20}$ eV cosmic ray seen

- **Low energy cosmic rays from Sun**
  - Solar wind (mainly protons)
  - Neutrinos

- **High energy particles from sun, galaxy and perhaps beyond**
  - Primary: Astronomical sources.
  - Secondary: Interstellar Gas.
  - Neutrinos pass through atmosphere and earth
  - Low energy charged particles trapped in Van Allen Belt
  - High energy particles interact in atmosphere.
  - Flux at ground level mainly muons: 100-200 s$^{-1}$
Cosmic Ray Spectrum

- **Flux follows power law**
  - $E^{-2.7}$ below knee
  - $E^{-3.2}$ below ankle

- **Energies up to $10^{20}$ eV**

- **Cosmic Rays at the surface**
  - Mostly muons
  - Average energy 4 GeV
  - Integrated Flux
    - 1 per cm$^2$ per minute for a horizontal detector
  - $\cos^2\Theta$ angular distribution
Muon Decay

- Muons decay \((\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu)\) with a mean lifetime of 2.2 \(\mu\)s
  - (mean lifetime = time for an assembly of decaying particles to be reduced by a factor of e)

- If a muon is created in the upper atmosphere (e.g. at \(h = 10\) km) does it make it to sea level?

- We would expect that even if the muons are traveling at close to the speed of light, the average distance they would travel before decaying is
  \[
  d = ct = (3 \times 10^8 \text{ m/s})(2.2 \times 10^{-6} \text{ s}) = 660 \text{ m}
  \]

- i.e. they would not make it to sea level

---

Special Relativity

- Wrong!

- According to special relativity, from our point of view time passes more slowly in a system that is in motion relative to us

- Thus, the moving muon "clock" ticks more slowly. This effect is called time dilation and is described by the simple formula

  \[
  t' = \gamma t \quad \text{where} \quad \gamma = \frac{1}{\sqrt{1 - v^2 / c^2}}
  \]

- Thus, the faster moving muons (e.g. those with speed \(v = 0.998c\)) will travel on average

  \[
  d' = ct' = \gamma ct = \left(\frac{1}{\sqrt{1 - 0.998^2}}\right)(660 \text{ m}) = (15.8)(660 \text{ m}) = 10.4 \text{ km}
  \]

- So, the faster moving muons make it to sea level!
Relativistic Kinematics

- Energy and momentum form a 4 vector \( p = (E, \mathbf{p}) \)
- The square of this 4 vector is the square of the rest mass of the particle. The rest mass is Lorentz invariant \( p^2 = E^2 - |\mathbf{p}|^2 = m^2 \)
- Define \( \beta = v/c \) and \( \gamma = (1-\beta^2)^{-1/2} \)
- Lorentz transformation

\[
\begin{pmatrix}
E^* \\
p^*
\end{pmatrix} = \begin{pmatrix}
\gamma & -\gamma \beta \\
-\gamma \beta & \gamma
\end{pmatrix}\begin{pmatrix}
E \\
p
\end{pmatrix}, \quad p^* \perp = p \perp
\]

- Natural units \( \hbar = c = 1, \hbar c = 197.3 \text{ MeV fm} \)
- Useful relations

\[
\gamma = \frac{E}{m} \quad \beta = \frac{p}{E} \quad \gamma \beta = \frac{p}{m}
\]
If neutrons were created in the center of our galaxy, with what momentum would they need to be produced in order to reach Earth before decaying? The distance between the center of our galaxy and the Sun is about 25,000 light years. The neutron has a mass of 940 MeV, and its lifetime is 886s.
Ultra High Energy Cosmic Rays

- Cosmic rays at the highest energy have galactic or even extra-galactic origin
- The universe is filled with the cosmic microwave background. Remnants of the Big Bang
- Photon temperature $\sim 2.7K$

Do you believe this result from the AGASA experiment?
Consider a high energy proton interaction with a photon of the cosmic microwave background. These photons are in thermal equilibrium with T~2.7 K corresponding to an energy of \(6.34 \times 10^{-4}\) eV. Find the minimum energy the proton would need for the following reaction to occur:

\[ p + \gamma \rightarrow \Delta^+ \quad (\rightarrow p + \pi^0) \]

Masses: \(p: 938\) MeV, \(\Delta: 1232\) MeV, \(\pi^0: 135\) MeV, \(\gamma: 0\)

Hint: \(P^2 = m^2\) (\(P = 4\)-vector), Lorentz invariant
Assume head-on collisions
GZK Cutoff

![Graph showing the energy spectrum of high-energy cosmic rays with a cutoff at a logarithmic scale. The graph illustrates the energy dependence of the differential flux, with data points from HiRes and Auger experiments, and fits using power laws and a smooth function.]
Four types of radioactive decay

1) alpha ($\alpha$) decay - $^4$He nucleus (2p + 2n) ejected
2) beta ($\beta$) decay - change of nucleus charge, conserves mass
3) gamma ($\gamma$) decay - photon emission, no change in A or Z)
   spontaneous fission - for Z=92 and above, generates two smaller nuclei
\( \alpha \) decay

\[
\frac{241}{95} Am \rightarrow^{\alpha} \frac{237}{93} Np + ^{4}_{2} He
\]

- involves strong and coulombic forces
- alpha particle and daughter nucleus have equal and opposite momentums (i.e. daughter experiences “recoil”)
- QM tunneling of alpha particle through potential barrier of the nucleus
- mono energetic (4-6 MeV)
- Short range (a few cm in air), stopped by paper
Radioactive Decay

- A household smoke detector
  - Small amount of Americium-241
  - Source of alpha particles
  - About 0.9 \( \mu \)Ci

- Ionization Chamber
β decay - three types

1) β⁻ decay

\[ ^3_1H \rightarrow ^3_2He + e^- + \bar{\nu}_e \]
- converts one neutron into a proton and electron
- no change of A, but different element
- release of anti-neutrino (no charge, no mass)

2) β⁺ decay

\[ ^{11}_6C \rightarrow ^{11}_5B + e^+ + \nu_e \]
- converts one proton into a neutron and electron
- no change of A, but different element
- release of neutrino

3) Electron capture

\[ ^7_4Be + e^- \rightarrow ^7_3B + \nu_e \]
- three body decay -> continuous spectrum
\[ \frac{3}{2}He^* \overset{\gamma}{\rightarrow} \frac{3}{2}He + \gamma \]

- conversion of strong to coulomb Energy
- no change of A or Z (element)
- release of photon, monochromatic
- usually occurs in conjunction with other decay

Spontaneous fission

\[
\begin{align*}
\frac{256}{100} \text{Fm} & \overset{sf}{\rightarrow} \frac{140}{54} \text{Xe} + \frac{112}{46} \text{Pd} + 4n \\
\end{align*}
\]

- heavy nuclides split into two daughters and neutrons
- U most common (fission-track dating)

Fission tracks from $^{238}$U fission in old zircon
- a radioactive parent nuclide decays to a daughter nuclide
- the probability that a decay will occur in a unit time is defined as \( \lambda \) (units of \( y^{-1} \))
- the decay constant \( \lambda \) is time independent; the mean life is defined as \( \tau = 1/\lambda \)

\[
\frac{dN}{dt} = -\lambda N \\
N = N_0 e^{-\lambda t} \quad \quad \lambda = \frac{\ln(2)}{t_{1/2}}
\]

Radioactive Decay Law

\( N_0 \) to \( N_0 / 2 \) to \( N_0 / 4 \) to \( N_0 / 8 \)
Activity

**Activity:**\[ A = -\frac{dN}{dt} = \frac{1}{\tau} \quad N = \lambda N \]

**Half life:**\[ T_{1/2} = \frac{\ln 2}{\lambda} = 0.693/\lambda \]

**Unit:**
1 Becquerel (Bq) = 1 decay per second

**Old unit:**
1 Ci (Curie) = Activity of 1 g of radium
1 Ci = \(3.7 \times 10^{10}\) Bq
1 Bq = 27 pCi

Smoke detector: 0.9 \(\mu\)Ci = 33,300 Bq

Human body: about 7,500 Bq (\(^{14}\text{C}, \quad ^{40}\text{K}, \quad ^{232}\text{Th}\))
On Sep. 19, 1991 a German tourist hiking in the Italian Alps found a Stone-Age traveler – the Ice Man or as we call him: Oetzi.

$^{14}\text{C}$ dating:

- Measured activity: $A = 0.121$ Bq/gram
- Half life: $T_{1/2} = 5730$ years
- Activity in a living organism: $A_0 = 0.23$ Bq/gram

How long ago did Oetzi die?
Dosimetry.

- The physical quantity responsible of physical and chemical changes in an irradiated material is the energy absorbed from the radiation field.
- Dosimetry provides a way to determine the amount of energy that has been absorbed by the irradiated material from the radiation.
- The dose $D$, is the amount of energy absorbed per unit mass of material.

$$ D = \frac{E}{m} $$
Gray (Gy) = J/kg
- the SI unit of measurement of dose
- one joule of energy is absorbed per kilogram of matter being irradiated
- 1 kGy = 1000 Gy

rad
- another common dose unit 1 rad = 100 erg/g
- 100 rad = 1 Gy
- A useful conversion factor between kGy and Mrads
  - 1 Mrad = 10 kGy.

Rem
- Dose unit used for radiation safety purposes.

Sievert (Sv)
- Include biological effectiveness
- Effective dose = dose * weight factor
- The SI unit of dose for radiation safety purposes
- 100 rem = 1 Sv; 100 mrem = 1 mSv
<table>
<thead>
<tr>
<th>Source</th>
<th>Dose (mSv/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmic radiation at sea level</td>
<td>0.26</td>
</tr>
<tr>
<td>Living in the Colorado Plateau</td>
<td>0.63</td>
</tr>
<tr>
<td>Food</td>
<td>0.40</td>
</tr>
<tr>
<td>Jet plane travel (4 h)</td>
<td>0.02</td>
</tr>
<tr>
<td>Chest X-ray</td>
<td>0.6</td>
</tr>
<tr>
<td>Dental X-ray</td>
<td>0.01</td>
</tr>
<tr>
<td>CAT Scan</td>
<td>1.1</td>
</tr>
<tr>
<td>Thyroid scan</td>
<td>0.14</td>
</tr>
<tr>
<td>Overall yearly dose</td>
<td>~2.5</td>
</tr>
<tr>
<td>Recommended occupational annual dose limit</td>
<td>20 (1 mSv for public)</td>
</tr>
</tbody>
</table>
Shielding

- Gamma rays
  - High Z material, e.g. Pb

- Electrons
  - Low Z material, e.g. polystyrene (High Z material leads to brems strahlung)
  - gamma ray shield for positrons (annihilation)

- Charged particles
  - High density material to maximize energy loss

- Neutrons
  - Hydrogenous materials such as water or paraffin
Homework

Take the Physics 780 Radiation Safety Refresher
Particle Accelerators

Particle Sources

For many applications we want monochromatic beams on demand

1. Make some particles
   - Electrons: metal cathode and some thermal energy
   - Protons and ions: Completely ionize gas

2. Accelerate them in the laboratory

\[ \text{K.E.} = e \times V \]
Creating Electrons

- Triode Gun
- Current: 1 A
- Voltage: 10 kV
- The grid is held at 50V below cathode (so no electrons escape).
- When triggered, grid voltage reduced to 0V. Electrons flow through grid.
- Pulse length: ~1ns
Circular or Linear?

- **Lorentz Force**
  \[ \vec{F} = e(\vec{E} + \vec{v} \times \vec{B}) \]

- **Linear Accelerator**
  - Electrostatic
  - RF linac

- **Circular Accelerator**
  - Cyclotron
  - Synchrotron
  - Storage Ring
DC Accelerators – Cockroft Walton

How it works

Cockcroft and Walton's Original Design (~1932)

- Voltage multiplier made of diodes and capacitors
- The first half cycle will load the first capacitor to its peak voltage. The second half cycle loads the second capacitor and so on...

Fermilab's 750kV Cockroft-Walton

- C&W used it to transmute Li with 700 keV protons into He and other elements
- Nobel prize in 1951
- DC accelerators quickly become impractical
- Air breaks down at ~1 MV/m
Van de Graaf Accelerator

Van de Graaf at MIT (25 MV)

- Proposed in 1929 to reach high voltages
- Charges are mechanically carried by conveyor belt from a low potential source to a high potential collector.
- Can reach several MV
Linear Accelerators

- DC electric fields beyond 20 MV are very difficult to achieve
- Proposed by Ising (1925)
- First built by Wideröe (1928)

- Replace static fields by time-varying periodic fields
- Use metal tubes to shield particles during “off-phases”
Cyclotron

- Utilise motion in magnetic field: 
  \[ p \ (GeV/c) = 0.3 \ q \ B \ R \]
- Apply AC to two halves
- Lawrence achieved MeV particles with 28cm diameter
- Magnet size scales with momentum…

- Still used for
  - Medical Therapy
  - Creating Radioisotopes
  - Nuclear Science

- Limitations
  - Relativistic effects
  - Uniformity of magnetic field

Berkeley (1929)

Orsay (2000)
Another solution to reach higher energies is to have several electrodes with alternating polarity.

Radio-frequency (RF) cavities use such AC field to accelerate particles to very high energies.

In a RF cavity the particles “surf” on an electromagnetic wave that travels in the cavity.
RF Cavities

- Particles travel in bunches
- (no DC beam)
- Always see an accelerating electric force
Keeping Particles in Bunches

Fill copper cavity with RF power
Phase of RF voltage (GHz) keeps bunches together

Up to ~50 MV/meter possible
SLAC Linac: 2 miles, 50 GeV electrons
It is possible to modify the principle of a cyclotron by replacing the electrodes with a much smaller RF cavity. The big magnet is replaced with a ring of smaller dipole magnets. Such a machine is called a synchrotron.
Synchrotrons

- \( p \ (GeV/c) = 0.3 \ q \ B \ R \)
- Cyclotron has constant \( B \), increasing \( R \)
- Increase \( B \) keeping \( R \) constant:
  - variable current electromagnets
  - particles can travel in small diameter vacuum pipe
  - single cavity can accelerate particles each turn
  - efficient use of space and equipment

- Discrete components in ring
  - cavities
  - dipoles (bending)
  - quadrupoles (focusing)
  - sextuples (achromaticity)
  - diagnostics
  - control

\[
\frac{mv^2}{2} = Bqv
\]

\[
\frac{v}{r} = \frac{Bq}{m}
\]

\[
f = \frac{Bq}{2m\pi} \frac{m_0}{m_0 + T}
\]
Two beams counter-circulating in same beam-pipe
Collisions occur at specially designed Interaction Points
RF station to replenish synchrotron losses
**Synchrotron Radiation**

- **Linear Acceleration**

\[
P_s = \frac{e^2 c}{6\pi \epsilon_0 (m_0 c^2)^2} \left( \frac{dE}{dx} \right)^2
\]

10 MV/m $\rightarrow$ 4 \(10^{-17}\) Watts

- **Circular Acceleration**

\[
P_s = \frac{e^2 c}{6\pi \epsilon_0 (m_0 c^2)^2} \frac{E^4}{R^2}
\]

Radius must grow quadratically with beam energy!
Functional Components of a Detector

- Decay scheme of $^{137}\text{Cs}$

Based on the level diagram, what do we expect to see?

Measured spectrum
Functional Components of a Detector

Characteristics
- Resolution
- Efficiency
- Sensitivity
- Deadtime
References used today

- Cosmic Rays, John Ellis
- World’s Greatest Scientific Instruments, D. Herzog
- Material from the books by Leo and Gruppen
- Introduction to Radiation Detector by H. Spieler
- Particle Data Book
- Introduction to Accelerators, E. Torrance