Outline

- What Is a Muon?
- Cosmic Origin and Interactions
- Muon Production and Path
- Effects in The Atmosphere
- Using Muons to Test Beam Profile Monitor
- Conclusion
What Is a Muon?

- Discovered in 1936
  - Carl D. Anderson and Seth Neddermeyer

- Fundamental Particle

- Similar to Electron
  - Lepton
  - Mass is ~207 Times That of the Electron
Interaction and Decay Modes

- Interaction
  - Gravitation
  - Electromagnetism
  - Weak Interaction

- Primary Decay Mode
  - $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$
  - $\sim 100\%$
## Fundamental Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon Mass</td>
<td>$105.6583668 \pm 0.0000038$ MeV</td>
</tr>
<tr>
<td>Muon Electric Charge</td>
<td>$e^-, e^+$ (anti-muon)</td>
</tr>
<tr>
<td>Mean Life</td>
<td>$2.19703 \pm 0.00004$ $\mu$ seconds</td>
</tr>
<tr>
<td>Spin</td>
<td>$1/2$</td>
</tr>
<tr>
<td>Magnetic Moment Ratio, $\mu/p$</td>
<td>$3.18334539 \pm 0.00000010$</td>
</tr>
<tr>
<td>Electric Dipole Moment</td>
<td>$3.7 \pm 3.4 (10^{-19} \text{ecm})$</td>
</tr>
</tbody>
</table>
Cosmic ray muons are created when high energy primary cosmic rays interact with earths atmosphere.

The primary sources of cosmic rays are supernovae.
Primary Cosmic Rays

- Components
  - 89% Hydrogen Nuclei (Protons)
  - Remaining 11% includes Helium, Carbon and Oxygen among other less abundant elements
Primary Cosmic Ray Interactions

- Gravitation
- Electromagnetism
Lorentz Force Law

- The equations of motion for primary cosmic rays interacting with earth’s magnetic field can be derived from the Lorentz force law.

\[ F = ma = q(v \times B) \]

- Manuel Vallarta
  - Earth is approximated as a magnetic dipole
High energy primary cosmic rays collide with atmospheric molecules at an altitude of ~ 15km to produce secondary cosmic rays.

Most abundant collisions:
- Proton $\rightarrow N_2$ Diatomic Molecule
- Proton $\rightarrow O_2$ Diatomic Molecule
Components of Secondary Cosmic Rays

- Protons, Neutrons, Pions, Kaons, Muons, Electrons and Photons
- Muons are the decay product of Pions and Kaons
  
  \[ \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \]
  
  \[ K^0 \rightarrow \pi^+ + \pi^- \]
The mean energy of muons at the site of production (~15 km alt.) is 6 GeV. This energy corresponds to a velocity of \(0.9998c\). This velocity is derived from the relativistic equation for energy

\[
E_{\mu}(\nu) = \frac{m_{\mu_0}c^2}{\sqrt{1 - \frac{\nu_\mu^2}{c^2}}}
\]
Path Through The Atmosphere

- **Time Dilation**
  - The lifetime of a 6 GeV cosmic muon as measured from Earth frame
    \[
    \tau = \gamma \tau_0 = 109.856 \times 10^{-6} \text{ s}
    \]

- The incident angle of the majority of muons at sea level is close to the zero zenith angle
  - \(~1\text{ muon/cm}^2\text{ minute}~\)
Effects in the Atmosphere

- Temperature Variance
- Interaction With Thunderstorms
Effects Cont’d

- Temperature Variance
  - Cosmic muon flux intensity corresponds directly with the atmospheric temperature at different pressures, altitudes and zenith angles
Interaction With Thunderstorms

- The mean muon flux intensity has been observed to decrease during and near thunderstorms.

- Lighting also affects the mean muon flux intensity during these thunderstorms.
Energy Loss In The Atmosphere

- Ionization and excitation processes
- Brehmsstralung
- Photonuclear and photonucleon interactions
- Primary mode of energy loss for low energy muons (~ 6 GeV) is through Ionization and Brehmsstralung
Testing the Beam Profile Monitor

- Thomas Jefferson National Laboratory
- PrimEx Experimental Setup

Beam Profile Monitor
Purpose of the Beam Profile Monitor (BPM)

- Determine the beam position and entrance angles as well as its’ spatial and angular divergence
- The detector is situated to measure the x and y coordinates of the incident photon beam (Horizontal and Vertical from the lab frame)
Internal structure of BPM (per module)
- ~ 64 Scintillating Fibers (2mm x 2mm x 13 cm)
- 4 groups of 16 light guides direct light into 4 photomultiplier tubes (PMT)
- 16 anode signals per PMT are processed by a discriminator
- One dynode signal per PMT
Photomultiplier Tube (PMT)

Discriminator
- Only allows anode signals that meet the prescribed parameters
Testing Cont’d

- **ECL Output**
  - Read on Scaler
  - Defined logical signal when event occurs

- **Analog Output**
  - Read on Oscilloscope
  - Shows a more detailed signal
Testing Cont’d

- Process
  - High voltage power supply ~ - 850 V per PMT
  - Low voltage power supply (electronic module)
  - Connect detector to Oscilloscope and Scaler
Testing Cont’d

- Setup
Testing Cont’d

- Process Cont’d
- Ensure detector is free from light leakage
- Check for faults
- Measure event rate on the scaler and event amplitude on oscilloscope
Testing Cont’d

- Data Retrieved
- Oscilloscope

- Significant electronic noise on module 3
  - Thermionic emission, leakage current
  - Significant after pulsing present
  - Residual gas, electrode glow
  - No light leakage
Confirmation of results

- Strong detection and signal processing on all channels of module 4
- Gain deficiency on module 3 PMT’s
- Further investigation required to determine exact cause of the problem
Testing Cont’d

- ECL Signals

- This data confirms the analog data
Summary of the test

- PMT 4 on module 3 does not produce any signal
- The discriminator for PMT 2 on module 3 requires adjustment
- The high voltage power supply must be individually adjusted for each PMT on both modules
- Each channel per PMT requires software calibration
Muons are fundamental particles that interact via gravitation, electro-magnetism and the weak interaction.

Cosmic muons are produced when primary cosmic rays interact with earth's atmosphere.

Muon flux and energy is effected by atmospheric conditions.

Muons are beneficial to modern scientific research.