General Information

- **General Information**
  - **Time:** Monday, Wednesday 12:30 - 2:18 PM
  - **Location:** PRB 3041
  - **Lecturer:** Prof. Klaus Honscheid
  - **Course Website:** [http://www-physics.mps.ohio-state.edu/~klaus/s12-780/phys780.html](http://www-physics.mps.ohio-state.edu/~klaus/s12-780/phys780.html)

- **Assessment**
  - **Homework problems** (20%)
  - **(short) paper with a presentation to the class** (40%)
  - **Hands-On: Measurement of the Muon Lifetime (if possible)** (40%)

- **Textbook**
  
  We will not follow any particular text book. However, most material covered in lecture (and more) can be found in any of these recommended resources.
  
  - Techniques for Nuclear and Particle Physics Experiments, W.R. Leo, Springer
  - Particle Detectors, 2nd ed., Grupen and Schwartz, Cambridge university Press
  - The Physics of Particle Detectors, Dan Green, Cambridge University Press
  - The Review of Particle Physics
    - [Free - request a copy at pdg.lbl.gov](http://pdg.lbl.gov)
    - Detector sections
  - As you might know, the world wide web was invented by particle physicists so it's not surprising that there is a lot of information on detector physics available on the net. Some of these links can be found in the reference section of these web pages.
Syllabus

- Introduction
  - Organizational Issues
  - Some basic concepts and examples
- Radioactive sources, Accelerators
- General Characteristics of Detectors
- Passage of Radiation through Matter
- Scintillation Detectors, Photomultipliers
- Pulse Signals, Electronics for Signal Processing
- Trigger Logic, Coincidence Technique, Time Measurements
- Gaseous Detectors
  - Ionization Counters
  - Proportional Chambers
  - Drift Chambers and Time Projection Chambers
  - Streamer Chambers
- Silicon Detectors
  - Principles
  - Strip and pixel detectors
  - Silicon Photomultiplier
  - CCDs
- Calorimetry
  - Electromagnetic Calorimeters
  - Hadronic Calorimeters
  - Cryogenic Detectors
- Particle Identification
  - Time of Flight
  - Cherenkov Effect and Detectors
  - Transition Radiation Detectors
  - Muon Identification, Momentum Measurement
  - Neutron Detection
  - (Neutrino Detectors)
- Data Analysis
  - Data Acquisition
  - Simulation
  - Statistical Treatment of Experimental Data
- Applications and Examples
- Student Presentations
Projects

- Muon Lifetime Measurement
- Individual Projects
Particle Physics – In 1 Slide

Atoms:
Neutrons & Protons, surrounded by Electrons

Pointlike objects, the fundamental building blocks as we now know them

Neutrons & Protons:
Each, built from 3 Quarks and held together by Gluons

~ Lanthanide Series
~ Actinide Series
Detector Basics

To be detected a particle has to live long enough to reach the detector

Particle Lifetimes  (see PDG for precise values and errors)

<table>
<thead>
<tr>
<th>Particle</th>
<th>Symbol</th>
<th>Mass</th>
<th>Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>e⁻</td>
<td>0.511 MeV</td>
<td>&gt; 4.6 x 10²⁶ years</td>
</tr>
<tr>
<td>Muon</td>
<td>μ⁻</td>
<td>105.6 MeV</td>
<td>2.2 x 10⁻⁶ seconds</td>
</tr>
<tr>
<td>Tau</td>
<td>τ⁻</td>
<td>1777 MeV</td>
<td>2.9 x 10⁻¹³ seconds</td>
</tr>
<tr>
<td>Neutrinos</td>
<td>ν</td>
<td>&lt; eV</td>
<td>&gt; 10²⁰ seconds</td>
</tr>
<tr>
<td>Quarks</td>
<td>u, d, c, s, t, b</td>
<td></td>
<td>no isolated quarks</td>
</tr>
<tr>
<td>Proton</td>
<td>p (uud)</td>
<td>938.2 MeV</td>
<td>&gt; 10²⁹ years</td>
</tr>
<tr>
<td>Neutron</td>
<td>n (udd)</td>
<td>939.6 MeV</td>
<td>881.5 seconds (free)</td>
</tr>
<tr>
<td>Pion</td>
<td>π⁺ (ud)</td>
<td>139.6 MeV</td>
<td>2.6 10⁻⁸ seconds</td>
</tr>
<tr>
<td></td>
<td>π⁰ (uu,dd)</td>
<td>135.6 MeV</td>
<td>1.6 10⁻¹⁷ seconds</td>
</tr>
<tr>
<td>Kaon</td>
<td>K⁺ (us)</td>
<td>493.7 MeV</td>
<td>1.2 10⁻⁸ seconds</td>
</tr>
<tr>
<td></td>
<td>K⁰ (uu,dd,ss)</td>
<td>497.7 MeV</td>
<td>5.1 10⁻⁸ s, 9.0 10⁻¹¹ s</td>
</tr>
<tr>
<td>Photon</td>
<td>γ</td>
<td>0</td>
<td>stable</td>
</tr>
</tbody>
</table>
# Detector Basics

- To be detected a particle has to interact with the detector

## Particle Interactions

<table>
<thead>
<tr>
<th>Particle</th>
<th>Symbol</th>
<th>Interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>$e^-$</td>
<td>weak, electromagnetic</td>
</tr>
<tr>
<td>Muon</td>
<td>$\mu^-$</td>
<td>weak, electromagnetic</td>
</tr>
<tr>
<td>Neutrinos</td>
<td>$\nu$</td>
<td>weak</td>
</tr>
<tr>
<td>Proton</td>
<td>$p$</td>
<td>weak, electromagnetic, strong</td>
</tr>
<tr>
<td>Neutron</td>
<td>$n$</td>
<td>weak, electromagnetic, strong</td>
</tr>
<tr>
<td>Pion</td>
<td>$\pi^+$</td>
<td>weak, electromagnetic, strong</td>
</tr>
<tr>
<td>Kaon</td>
<td>$K^+ (us)$</td>
<td>weak, electromagnetic, strong</td>
</tr>
<tr>
<td></td>
<td>$K^0_L$</td>
<td>weak, electromagnetic, strong</td>
</tr>
<tr>
<td>Photon</td>
<td>$\gamma$</td>
<td>electromagnetic</td>
</tr>
</tbody>
</table>
Particle Physics Conventions

- Energies are measured in eV (MeV, GeV, TeV...)
  - $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$

- A particle’s momentum is measured in MeV/c

- A particle’s mass is measured in MeV/c$^2$

- Using $E = mc^2$ for an electron:
  - $m_e = 9.1 \times 10^{-31} \text{ kg}$
  - $E_e = m_e c^2 = 9.1 \times 10^{-31} (3 \times 10^8)^2 \text{ kg m}^2/\text{s}^2$
    - $= 8.2 \times 10^{-14} \text{ J}$
    - $= 0.511 \text{ MeV}$
Muons – Always good for a surprise

The wiggles below go faster than prediction.

This EXCITES Physicists like you wouldn’t believe!

Time called the muon “a winner!”
Cosmic Rays

Energies from $10^6$ – $10^{20}$ eV

Courtesy Mats Selen
Consider exotic violent events in the Cosmos as noted by very energetic cosmic rays

Record energy is a proton of \(3 \times 10^{20} \text{ eV} \) (48 J)
Equivalent energy of a

- Roger Clemens fastball,
- Tiger Woods tee shot,
- Pete Sampras tennis serve,
- speeding bullet.

And, all just one proton

WHERE ARE THE COSMIC ACCELERATORS OF SUCH PARTICLE FASTBALLS ????

Courtesy Tom Weiler, Vanderbilt University
About 200 $\mu$'s per square meter per second at sea level.

(lots of neutrinos too...)
Some typical values

- **Cosmic Ray Flux on the surface**
  - Mostly muons, $<E> \sim 4$ GeV
  - Intensity $\sim 1$ cm$^{-2}$ min$^{-1}$ for a horizontal detector

- **Neutrino Flux**
  - Solar Neutrinos
  - $6.5 \times 10^{10}$ cm$^{-2}$ min$^{-1}$ (perpendicular to direction to sun)
With the right instrument we can detect muons and other particles.

- **Plastic scintillator**
  - Gives off a flash of light when a charged particle passes through.

![Diagram showing the setup with a plastic scintillator, photo-multiplier, and oscilloscope.](image)
A typical physics class might ...

... catch some muons from cosmic rays,

and, measure how long they live

Answer: 2 millionth's of a second
How is the muon lifetime measured?
How is the muon lifetime measured?
How is the muon lifetime measured?

N=100
How is the muon lifetime measured?

\[ \chi^2 / \text{ndf} = 8.309 / 82 \]
\[ N_0 = 1.117 \pm 0.162 \]
\[ \tau = 9.664 \times 10^4 \pm 426545 \]

N=100
How is the muon lifetime measured?

\( N = 10^4 \)

\( \chi^2 / \text{ndf} \quad 488.3 / 544 \)
\( \bar{N} \quad 91.94 \pm 1.38 \)
\( \tau \quad 2090 \pm 23.9 \)
How is the muon lifetime measured?

\[ \chi^2/\text{ndf} = 1082/966 \]

\[ N_0 = 9125 \pm 12.9 \]

\[ \tau = 2190 \pm 2.2 \text{ ns} \]

\[ N = 10^6 \]
How is the muon lifetime measured?

\[ \delta\tau = 2.207 \times 10^{-3} \]

\[ N = 10^{12} \]
How long will it take?

- $\sim 10^{12}$ events necessary for 1 ppm measurement
  (relative error $\sim 1/\sqrt{n}$)

<table>
<thead>
<tr>
<th>Source</th>
<th>Muon rate</th>
<th>Time to $10^{12}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmic rays</td>
<td>$1 / 50 \text{ cm}^2 \text{ s}$</td>
<td>$\sim 10^4$ years</td>
</tr>
<tr>
<td></td>
<td>$1 / \text{ hand s}$</td>
<td></td>
</tr>
<tr>
<td>Continuous beam</td>
<td>20 kHz</td>
<td>$\sim 1.6$ years</td>
</tr>
<tr>
<td></td>
<td>$1 / 50 \mu\text{s}$</td>
<td>beam time</td>
</tr>
<tr>
<td>Pulsed beam</td>
<td>$22 / 32 \mu\text{s}$</td>
<td>$\sim 3$ weeks</td>
</tr>
<tr>
<td></td>
<td>(usable)</td>
<td>beam time</td>
</tr>
</tbody>
</table>
Muon Lifetime Experiment

Goals: Measure the lifetime of the muon ($\mu$) to ~2% precision
Gain hands-on experience with detectors, electronics, data

Break up into groups of 2 or 3
Each group spends a few days with the experiment in Smith Lab

Report written using LATEX (Develop your scientific writing skills)

Report should include a section on:

- Introduction
- Apparatus
- Theory
  - calculation of muon lifetime
  - Discussion of higher order correction
  - Lifetime of free $\mu$ Vs captured $\mu$
- Data Analysis
  - Determination of average $\mu$ lifetime
  - Possible separation into $\mu^+$ and $\mu^-$ lifetimes
  - Upper limit on the amount of a particle with lifetime=4$\mu$s in data
  - Background estimation
- Systematic errors
- Conclusions
- References

Reports are due before end of the winter quarter

This is a typical senior lab experiment. Search the Web for lots of information on muon lifetime measurements.
Projects

- **Muon Lifetime Measurement**
- **Individual Projects**

While many of the detector concepts that we will discuss in this course have first been developed for particle and nuclear physics experiments, these instruments are now used for a large variety of applications.

**Your task:**

- Identify an interesting detector application
- Research this topic using the web, the library, local resources in the physics department
- Write a 5-10 page report in the style of a research paper
- Prepare a 20-30 minute presentation on your paper and the application you have investigated

The next set of slides should give you some ideas
Example Projects

- Homeland Security

  **James Bond**
  If you think a device that resembles a cellular phone but detects a potential nuclear threat and transmits a description of the nuclear material to every nearby crisis center sounds like something out of a James Bond movie, you are in for a surprise. Since the 1930s, when scientists first used the Geiger counter, radiation detection equipment has gone through an amazing evolution in size, sensitivity, deployability, and power. (From DOE web site)

  **Baggage Scanners**
  Conventional x-ray baggage scanners in airports employ a dual energy x-ray approach in order to view different materials. A new approach has been employed to increase the identification of materials. This involves performing x-ray diffraction analysis on baggage as it passes through the scanner.

  **Scanning Trucks** (e.g. Neutron Activation Analysis)
Example Projects

- **CVD Diamond Detectors**
  
  Developed by our own Harris Kagan
  
  Extremely radiation hard: Beam monitor applications
Example Projects

- **Imaging Cherenkov Detectors**
  - Cherenkov Correlated Timing Detector
  - BaBar DIRC
  - Belle TOP
Example Projects

- Neutrino Detectors
  - Principles
  - Minos, Nova
  - Reactor Experiments
- Deep Underground Detectors
  - SNO
  - DUSEL
  - Direct Dark Matter Searches
- Example: Super Kamiokande

Put far underground (2700m H$_2$O) to shield against cosmic rays
Some neutrino facts

- The Sun produces many neutrinos when it burns
- The Big Bang left us ~ 300 neutrinos per cubic cm that are still running around
- Power reactors make lots of neutrinos
- ALL neutrinos are very hard to detect.
  - Need enormous mass to catch just a few
- Fill space between the earth and sun with lead
  - Less than 1 out of 10,000 neutrinos would notice!

![Diagram of lead between Earth and Sun]
Control Room

Entrance 2 km

Control Room

Tank

Linac cave

Water System

Outer Detector

Inner Detector

Put far underground (2700m H₂O) to shield against cosmic rays

Mt. Ikeno

The Super Kamiokande Detector
Nov. 13 2001: Bottom of the SK detector covered with shattered PMT glass pieces and dynodes. 1/3 of PM destroyed

13000 large PM
Use a boat for maintenance + installation
Be careful
2002 Nobel Prize: Neutrino Oscillation results from SuperK

Cosmic Ray protons illuminate the earth evenly from all directions.

These produce lots of $\nu$'s when they crash into Earth's atmosphere.

Super-K studied these atmospheric neutrinos as a function of direction...
Half as many are observed from below as from above.

Super-K Results

It means they morph and it means they have mass:

All Textbooks have now had to be rewritten...
Example Projects

- Instrumentation for Space Based Experiments
  
  **GLAST/FERMI**
  **SNAP/JDEM**

  **A high energy physics experiment in space**

  **Study γ-rays from 20 MeV-300 GeV**

  **Measure energy and direction**
  
  Dark matter annihilation
  Gamma ray bursters
  Active Galactic Nuclei

  **Si Tracker**
  
  pitch = 228 µm
  8.8 $\times$ 10^5 channels
  12 layers $\times$ 3% $X_0$
  + 4 layers $\times$ 18% $X_0$
  + 2 layers

  **CsI Calorimeter**
  
  Hodoscopic array
  8.4 $X_0$, 8 $\times$ 12 bars
  2.0 $\times$ 2.7 $\times$ 33.6 cm
  
  ⇒ cosmic-ray rejection
  ⇒ shower leakage correction

  **ACD**
  Segmented scintillator tiles
  0.9997 efficiency

  **Size**: 1.8x1.8x1m
Example Projects

- Bolometers: Analyzing the Cosmic Microwave
Example Projects

- Application of Particle Detectors in Medical Imaging Devices
  - SPECT Camera
  - Compton Camera
  - PET
  - Combined PET/MRI Scanner
Projects

- Muon Lifetime Measurement
- Individual Projects, List of Topics
  1. Detectors for Homeland Security
  2. Diamond Detectors
  3. Monte Carlo Simulation
  4. Trigger and Data Acquisition
  5. Combined PET/MRI Scanner
  6. Instrumentation for (Synchrotron) Light Sources
  7. Digital Calorimeter
  8. Bolometer
  9. Compton Camera
  10. Cherenkov Detectors using Total Internal Reflection
  11. Radiation Hardness
  12. New Photon Detectors (APD, Silicon PM etc)
  13. Detectors for Astrophysics (GLAST, Auger, Veritas)
  14. Deep Underground Detectors (Dusel)
  15. Neutrino Detectors
  16. Electronics, FPGA
  17. Cryogenic Detectors
  18. Detectors for Cosmology, CCDs
  19. <Insert Your Idea Here>
References used today

- Measurement of the Positive Muon Lifetime to 1 ppm, D. Webber
- World’s Greatest Scientific Instruments, D. Herzog
- Experimental Techniques of High Energy, Nuclear, & AstroParticle Physics, R. Kass