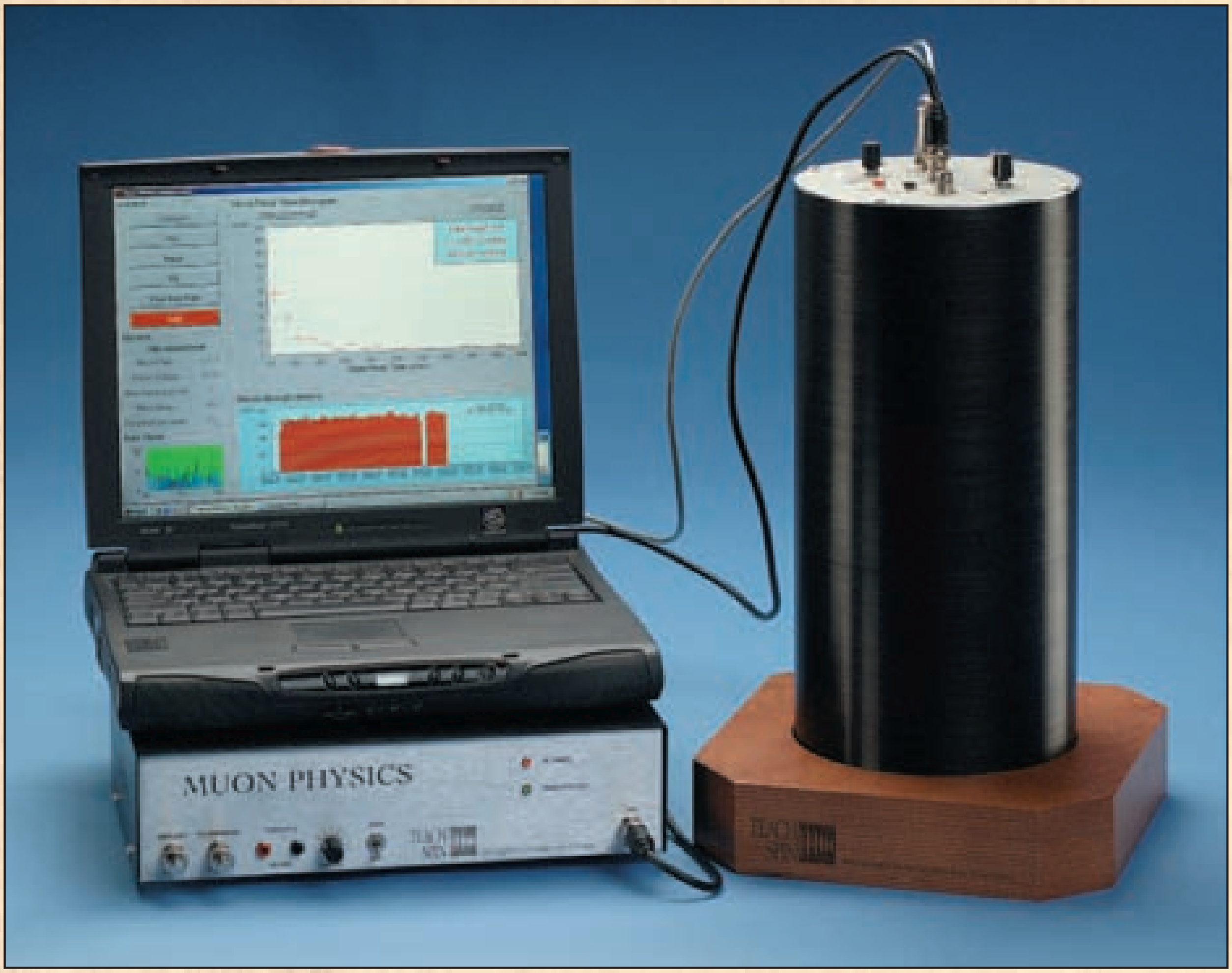
MUON PHYSICS



"Catching" Cosmic Rays

- Measure Muon Lifetime
- Demonstrate Relativistic Time Dilation
- Measure Local Muon Flux
- Measure Sea Level Muon Charge Ratio
- Convenient Source of Genuinely Random Numbers
- Create Simulated "Muons" and Measure their Lifetime
- Study Processing of Photomultiplier Signal

Instruments Designed For Teaching

TEACH SPIN

The 1937 discovery of the muon by Carl Anderson marked a radical departure in physicists' understanding of the building blocks of matter. Although it was first assigned a place in the theory of nuclear forces which was incorrect, the muon is now understood to be an important member of the lepton family of fundamental particles.

In collaboration with Thomas Coan and Jingbo Ye of Southern Methodist University, TeachSpin has built the first commercial teaching instrument for students to determine some of the muon's physical characteristics. It can be used anywhere from an advanced laboratory where students will want to create their own algorithms for determining muon lifetime and explore the workings of the photomultiplier, to a high school science class participating in a national or international comparative muon flux project.

Muons are produced copiously in Earth's upper atmosphere by interactions between cosmic rays and atmospheric air molecules. Their flux at sea level is sufficient for student investigations. The muon's ***lifetime*** can be measured with our apparatus using experimental techniques common to both nuclear and particle physics. The ***stopping rate*** of muons in our detector, as a function of depth in the atmosphere, can be used as a demonstration of the ***time dilation*** effect of special relativity. Also, since the decay times of individual radioactive particles are randomly distributed, they are a convenient source of genuinely random numbers. These can be used to demonstrate ***common probability distributions***.

THE INSTRUMENT

Three "modules" comprise the Muon Physics hardware: the detector, the electronics, and a user supplied computer. Figure 1 shows the block diagram. Data processing software, written by Coan and Ye, runs on both Microsoft Windows and Linux. Updates will be available via the web. The program requires 100 Mbytes of disk space (mostly for data storage) and 32 Mbytes of memory. The PC processor should be equivalent to an Intel 133 MHz or better.

Detector Module:

A black anodized aluminum cylinder houses the entire detector module including the plastic scintillator, photomultiplier tube (PMT), and high voltage supply (HV) as well as electronics for an embedded LED. The scintillator, a right circular cylinder, is optically coupled to a single 5 cm diameter 10-stage PMT. Because all of the circuitry for the PMT is mounted inside the aluminum cylinder, there are no exposed HV electrodes. The HV is manually varied and monitored by external controls. The scintillator is sufficiently thick that muon passage through, or decay inside, produces ample light to be detected by the PMT. The embedded LED can be driven by the adjustable pulser to mimic muon decays and to test the readout and storage electronics.

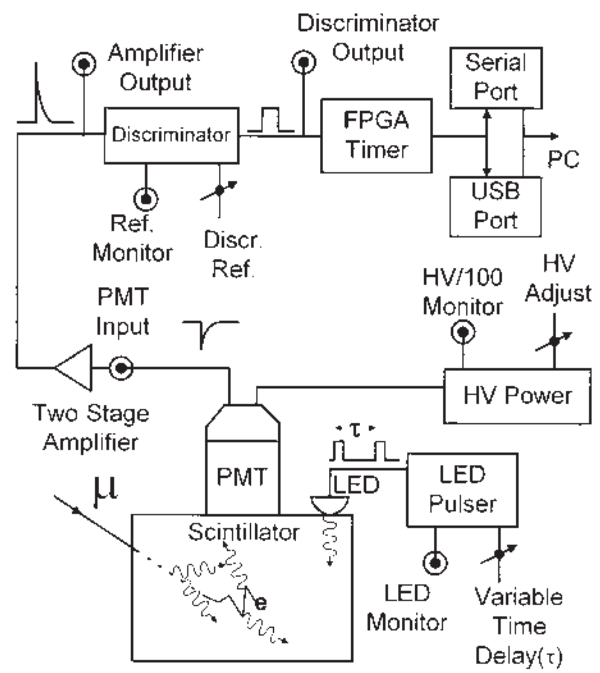


Figure 1

Electronics Module

The electronics module houses all electronics needed to run the experiment. PMT pulses are first amplified and compared against an adjustable threshold. Pulses above threshold are sent to timing circuitry implemented in a field programmable gate array (FPGA) chip. (See Figure 2.) The first flash of the scintillator starts the timing system. If a second flash occurs within 20 microseconds of the first, the readout electronics measures the time between the two flashes and passes that time to the lifetime display software.

If a second flash does not occur within 20 microseconds, the pulse is simply recorded as a charged particle that has passed through the detector. Communication circuitry transfers the data to a PC or laptop through either a serial or USB port.

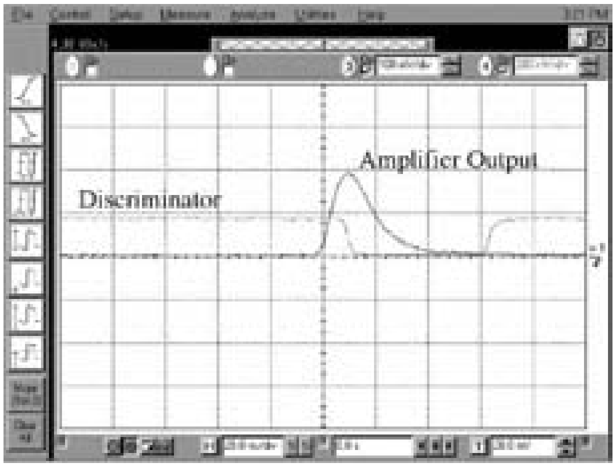


Figure 2

Connections on the front panel allow students both to examine the PMT signal itself, and to monitor that signal as it moves along the readout chain.

The Software

Data acquisition of muon decay times is computer controlled to eliminate the tedium of number recording and to permit extended data collection. The decay time histogram is automatically updated with data from the readout electronics. Important display features like the histogram's bin size and the logarithmic/linear axis type remain under user control. A password-protected built-in curve fitting algorithm allows for easy determination of the muon lifetime while still maintaining instructor control. Various rate monitors indicate quantities like the instantaneous and time averaged trigger rate, the total number of recorded muon decays and the elapsed time for data acquisition.

Raw data are written to disk files in a compact format so that students can export them to their own software package and not rely on the one provided. Simulation software allows the creation of decay time distributions with a user-adjustable muon lifetime. Source code for data acquisition, plotting and simulation is written in the Tcl/Tk scripting language and is provided free of charge so motivated students can modify the user interface or the built-in lifetime curve fitting algorithm Software is distributed on a CD and runs under Microsoft and Linux operating systems. Free updates are available via the World Wide Web.

STUDENT EXPERIMENTS

Mean Muon Lifetime

The form of the decay time distribution for muons stopped in the scintillator is characteristic of the decay of radioactive substances with some background counts. This is mathematically expressed as:

$$N(t) = N_o e^{-\frac{t}{\tau}} + B$$

Additional background counts can be easily induced by bringing a 1 micro-Curie Cs-137 source close to the detector. After measuring and plotting the distribution of times between successive scintillator flashes, students can fit the exponential-like distribution and extract the **mean muon lifetime** (τ) in matter, using either our curve fitting algorithm or their own.

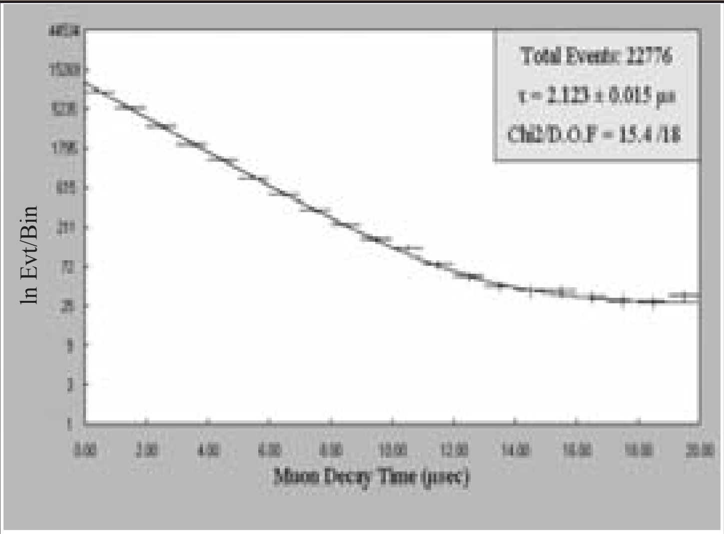


Figure 3

The screen capture in Figure 3 was made using the included software and shows a fit to actual student data. Note that the central value for the muon's lifetime, $\tau = 2.123 \pm 0.015$ μsec, is less than the free space value, $\tau = 2.197 \pm 0.001$ μsec. This correctly indicates the effect of nuclear interactions between protons and negative muons.

Once the muon lifetime is measured, a value of the Fermi coupling constant G_F, characterizing the strength of the weak interactions, is easily determined.

G_F is calculated from:

$$\frac{192\pi^3}{G_F{}^2 m_\mu{}^5}$$

Accounting only for statistical error, the student data shown yields $G_F = (1.18 \pm 0.01) \times 10^{-5}$ GeV^{-2}, which is consistent with more precise measurements.

Sea-level Charge Ratio

With this instrument, the muon lifetime measured in matter (i.e., plastic scintillator) is an average over negatively and positively charged muons. Negatively charged muons have nuclear interactions that slightly lessen their mean lifetime in matter. Therefore, using the lifetime of negative muons in carbon taken from the literature ($\tau = 2.043 \pm 0.003$ μsec), the sea-level charge ratio of positive to negative muons at low energy, $E_\mu \cong 200$ MeV, can be easily determined. The student data included in this brochure yields a sea-level charge ratio $f_+/f_- = 1.08 \pm 0.01$ (32.5° latitude), which is consistent with published values.

Time Dilation Effect of Special Relativity

Once the muon lifetime is measured, the stopping rate as a function of elevation above sea level can be used to distinguish between the predictions of classical mechanics and special relativity, providing confirmation of the time dilation effect of special relativity. Although the instrument is not optimized for this measurement, the simplicity of the measurement is appealing since it requires no lead shielding. For example, after measuring the muon stopping rate to a statistical precision of 2% at two locations vertically separated by 1985 meters, the ratio of these stopping rates (0.55 ± 0.02) agrees well with a straightforward calculation (0.56 ± 0.06) that accounts for time dilation, muon energy loss in the atmosphere, and the differential muon momentum spectrum at sea level.

Cosmic Ray Background Radiation

Included rate monitors measure both the stopping rate of muons and the combined total charged particle flux (which includes both muons and electrons) that pass through the scintillator. This data can be used to monitor variations in cosmic radiation at the geographic location of the observer.

Predictions of Probability Theory

The decay times of individual muons are an excellent source of genuinely random numbers. Once the exponential form of the probability distribution for these times is measured, students can make predictions about the outcomes of corresponding binomial experiments. Taking a new data set then allows a direct comparison between actual data and the predictions of probability theory.

Explore Processing of Photomultiplier Signal

Test points are provided along the entire electronic signal chain so that students can examine the waveforms of the photomultiplier signal, either real or simulated, at various stages of processing. The photomultiplier high voltage, the amplifier gain, the threshold setting and the FPGA timing characteristics are easily measured with an oscilloscope or voltmeter.

SPECIFICATIONS

Detector Size: Diam. 16.5 cm Height 35.5 cm

PMT: 10-stage bialkali photocathode Diam. 5.1 cm

Timing FPGA: Bin Size (resolution) 20 ns
Dynamic Range 20 μsec

Timing clock frequency: 50 MHz ± 5 kHz

Power Consumption (excluding PC): 25 watts

Typical detected muon decay rate: 1 event/minute

Operating systems: Microsoft Windows™ 95, 98, ME, 2000, XP and Linux

Supported I/O port protocols: Serial and USB

Free Software Upgrades

Detector and Electronic Modules available separately

Recommended minimum PC performance

Processor: Intel 133 MHz

Disk Space: 100 Mbytes

Memory: 32 Mbytes

Electronics Case: 11x7x3 inches

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