

# Measuring the Lifetime of the Muon Particle

Austyn Young

# Quantum Field Theory

Small →

Fast  
↓

Classical mechanics e.g. $F = ma$	Quantum mechanics e.g. Heisenberg uncertainty principle
Relativistic mechanics e.g. $E = mc^2$	Quantum Field Theory e.g. force carriers (or mediators)

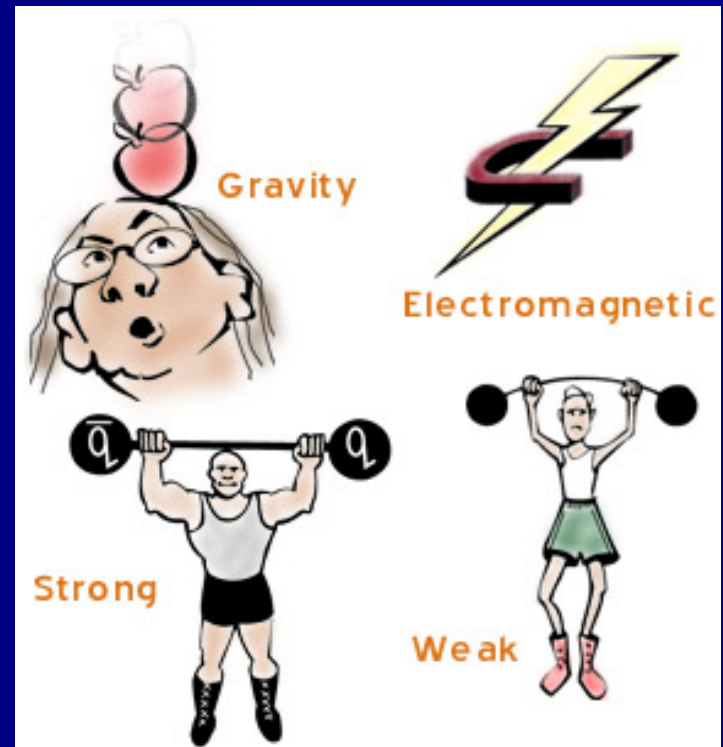
# The Four Forces in Nature

Long range:

- Gravitational
- Electromagnetic

Short range:

- Strong (binds atomic nuclei together)
- Weak (responsible for radioactive decay)



# Quantization of the force field

- Forces can be understood as a result of:
  - (1) Force field (e.g., EM field)
  - (2) Exchange of force carrier particles (e.g., photons exchanged between electrons)

# Force carriers

- Each of the four forces has a force carrier(s)

	Gravity	Weak (Electroweak)	Electromagnetic	Strong
Carried By	Graviton (not yet observed)	$W^+$ $W^-$ $Z^0$	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and $W^+$ $W^-$	Quarks and Gluons

# Early theory of strong force

- What holds the nucleus together?  
(EM repulsion between protons in the nucleus)
- Hideki Yukawa predicted the existence of a particle that would mediate the strong force—the meson (1934)

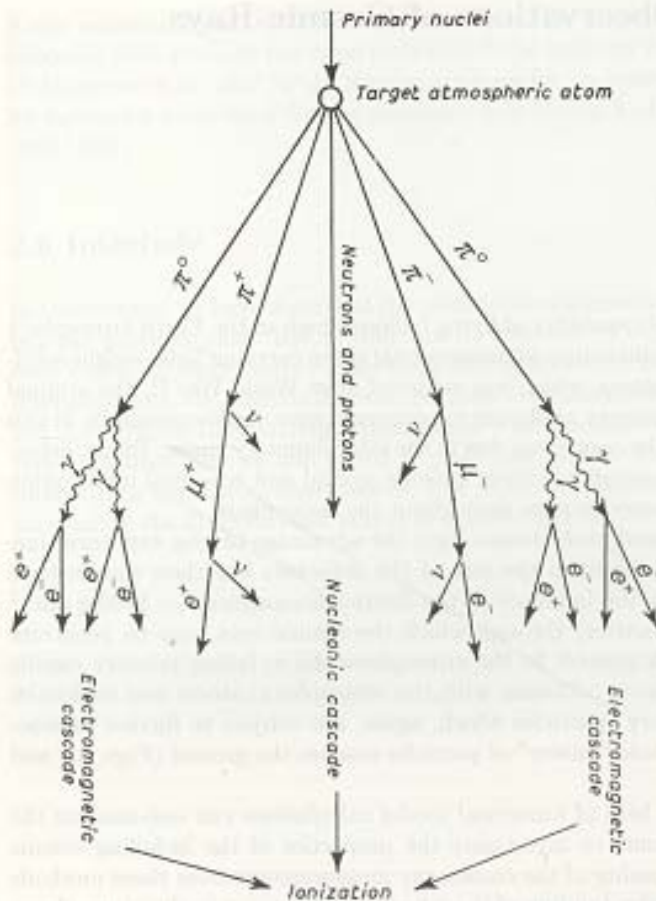
# Early theory of strong force

- Muon was discovered in 1936 and mistaken for the meson
- Meson was finally discovered in 1947
- Yukawa's particle is now known as a pion

# The Standard Model

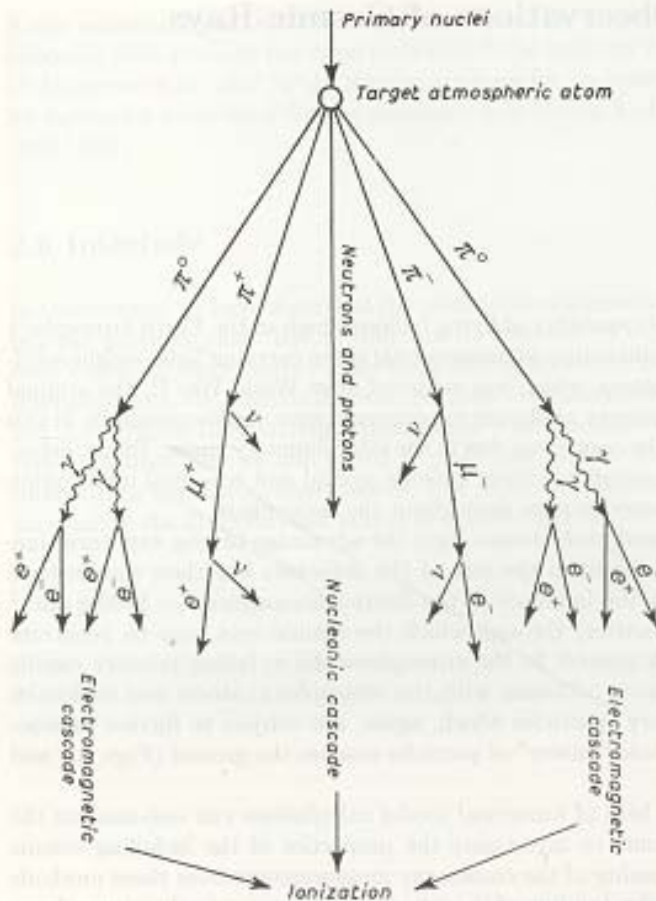
Fermions		Bosons	
Leptons	electron neutrino ( $e$ ) <b>muon</b> neutrino ( $\mu$ ) tau neutrino ( $\tau$ )	Gauge bosons (force carriers)	photon $W^\pm$ Z Gluon
Hadrons			
Baryons (qqq)	proton neutron	Mesons (qq)	pion

# Cosmic Rays

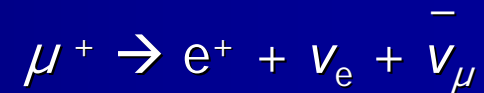
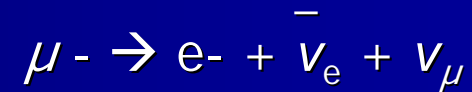


- High energy particles from outside Earth's atmosphere
- Primary cosmic rays enter atmosphere and collide with atoms
- Produce showers of secondary cosmic rays (e.g., pion and muon)

# Cosmic Ray Muons



- Muon decays into an electron and neutrinos:



- Average lifetime of muon decay:

$$\tau_\mu \approx 2.2 \times 10^{-6} \text{ s}$$

# Time dilation

- Muon reaches ground because of time dilation
- Einstein's relativity theory: as a particle approaches speed of light, its lifetime is measured to be longer than when it is at rest by a factor  $\gamma$
- $t = \gamma T = \tau / [1 - v^2/c^2]^{1/2}$

# Worked-out Example

- **Ex.** What is the lifetime of muon traveling at  $v = 0.60c = 1.8 \times 10^8$  m/s relative to an observer? How far does the muon travel before decaying?
- $t = \gamma T_{\mu} = 2.2 \mu\text{s} \div [1 - 0.36 c^2/c^2]^{1/2}$   
 $\therefore t = 2.8 \mu\text{s}$
- $\lambda = vt = (1.8 \times 10^8 \text{ m/s}) \times (2.8 \times 10^{-6} \text{ s})$   
 $\therefore \lambda = 500 \text{ m}$

# Why do muons decay?

<b>Generation</b>	<b>Particle name</b>	<b>Symbol</b>	<b>Rest Mass (MeV/c<sup>2</sup>)</b>	<b>Lifetime (s)</b>
First	Electron	$e^-$	0.511	Stable
	Neutrino (e)	$\nu_e$	$<4 \times 10^{-6}$	Stable
Second	Muon	$\mu^-$	105.7	$2.20 \times 10^{-6}$
	Neutrino ( $\mu$ )	$\nu_\mu$	$<0.17$	Stable
Third	Tau	$\tau$	1777	$2.91 \times 10^{-13}$
	Neutrino ( $\tau$ )	$\nu_\tau$	$<18$	Stable

# Muon Decay

- Lifetime depends on which force is predominant in decay
- Muon decay is a weak force decay:

$$(1) \mu^- \rightarrow \nu_\mu + W^-$$

$$(2) W^- \rightarrow e^- + \bar{\nu}_e$$

# Radioactive Decay

- Rate of decay, or number of decays per second, in a sample is:

$$A(t) = A_0 e^{-t/\tau}$$

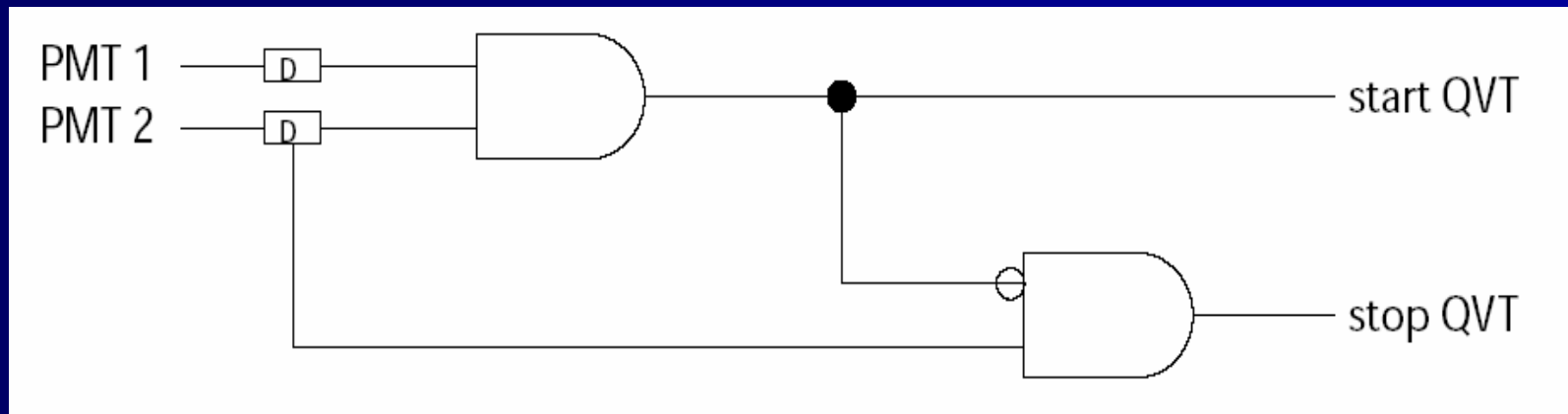
- $A_0$  is initial rate of decay at  $t = 0$
- $A(t)$  is rate after a time  $t$
- $\tau$  is lifetime of particle

# Experiment

- Measure muon lifetime  $\tau_\mu$
- Method: plot rate of muon decay versus time
- We expect the rate to decrease exponentially in time:

$$A(t) = A_0 e^{-t/\tau_\mu}$$

# Experimental Setup

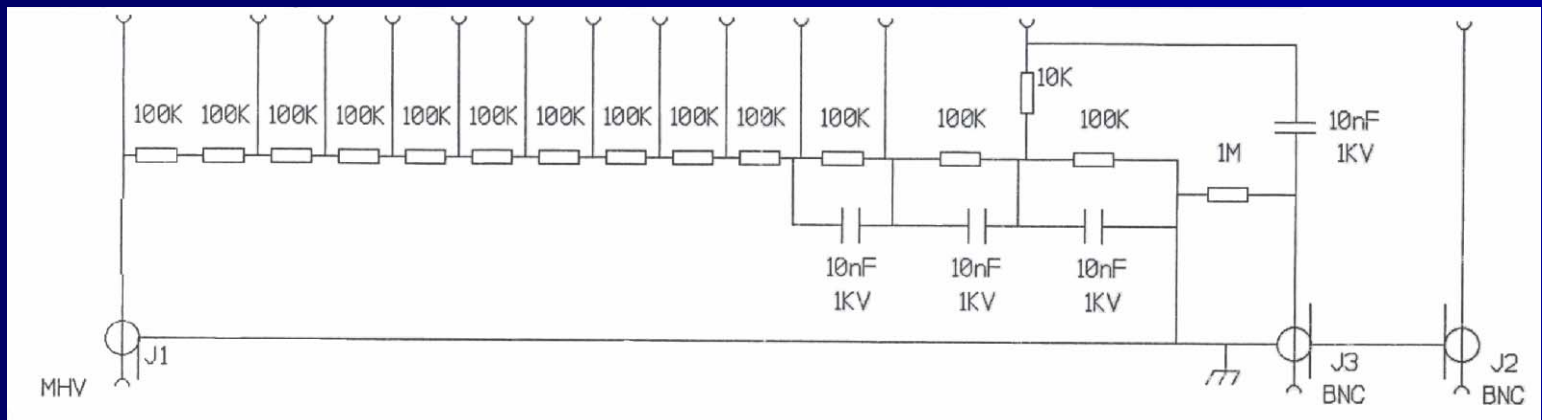


## Coincidence circuit

- Scintillator
- Photomultiplier tube (PMT)
- Discriminator (D)
- Coincidence gate
- Anticoincidence gate
- QVT pulse analyzer

# Photomultiplier tube (PMT)

- Photocathode releases electrons when struck by scintillator emitted photons
- Electrons accelerated through a series of dynodes
- Dynodes release secondary electrons
- → Amplification of signal



# QVT pulse analyzer

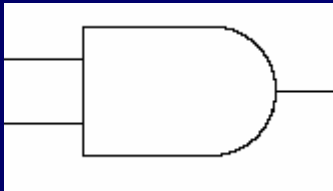
- Receives muon (start) and electron (stop) pulses
- Measures time interval between pulses
- Histograms time intervals in a plot of decay rate versus time:

$$A(t) = A_0 e^{-t/\tau_\mu}$$

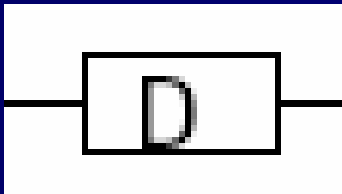
- From this histogram, we can determine the mean muon lifetime  $\tau_\mu$

# Noise Reduction

- Coincidence circuit

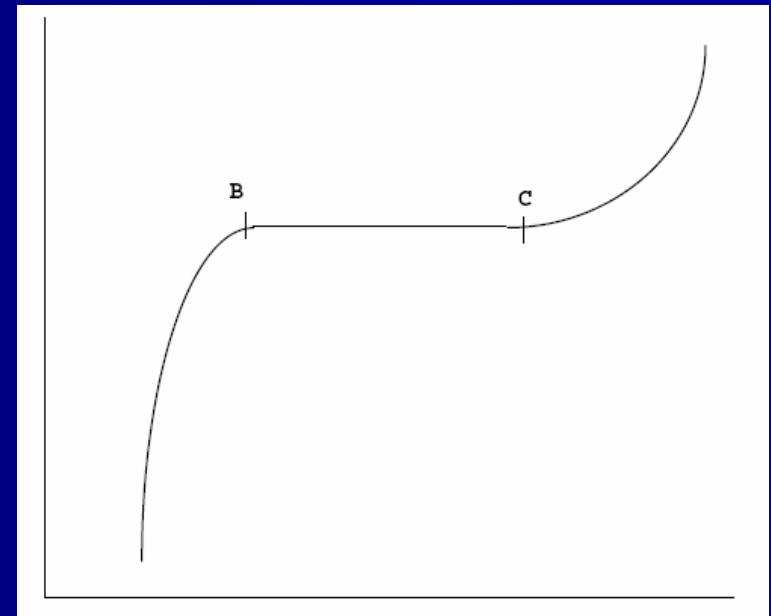


- Discriminator



- PMT voltage power supply

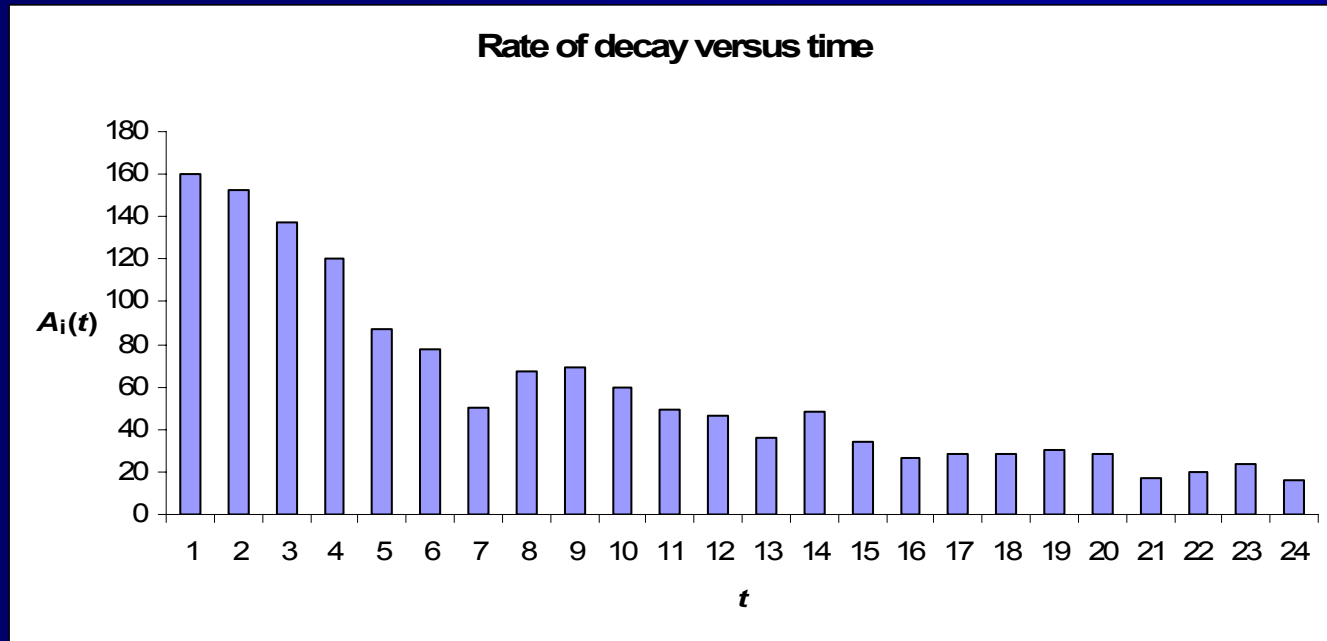
PMT counting rate



Applied Voltage

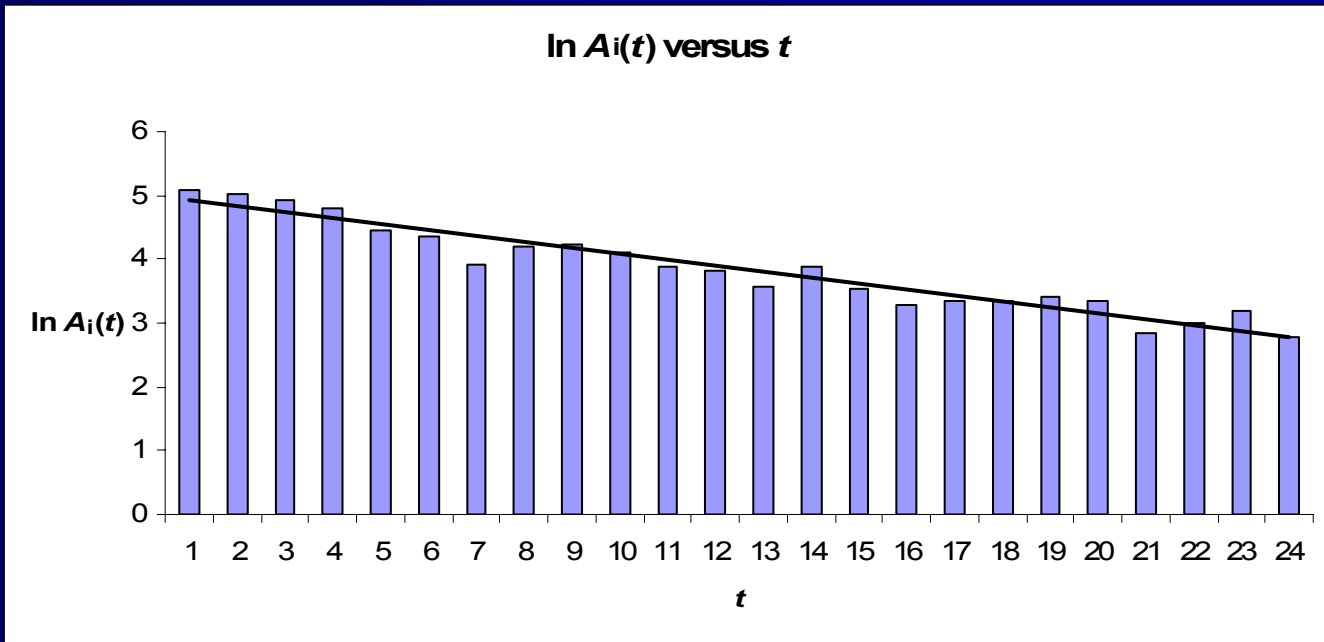
# Results

- Is data fit by exponential  $A(t) = A_0 e^{-t/\tau_\mu}$ ?



# Fitting Function

- $\ln A(t) = \ln A_0 + (-1/\tau_\mu) t$



# Solving for parameters

- $\ln A(t) = \ln A_0 + (-1/\tau_\mu)t$

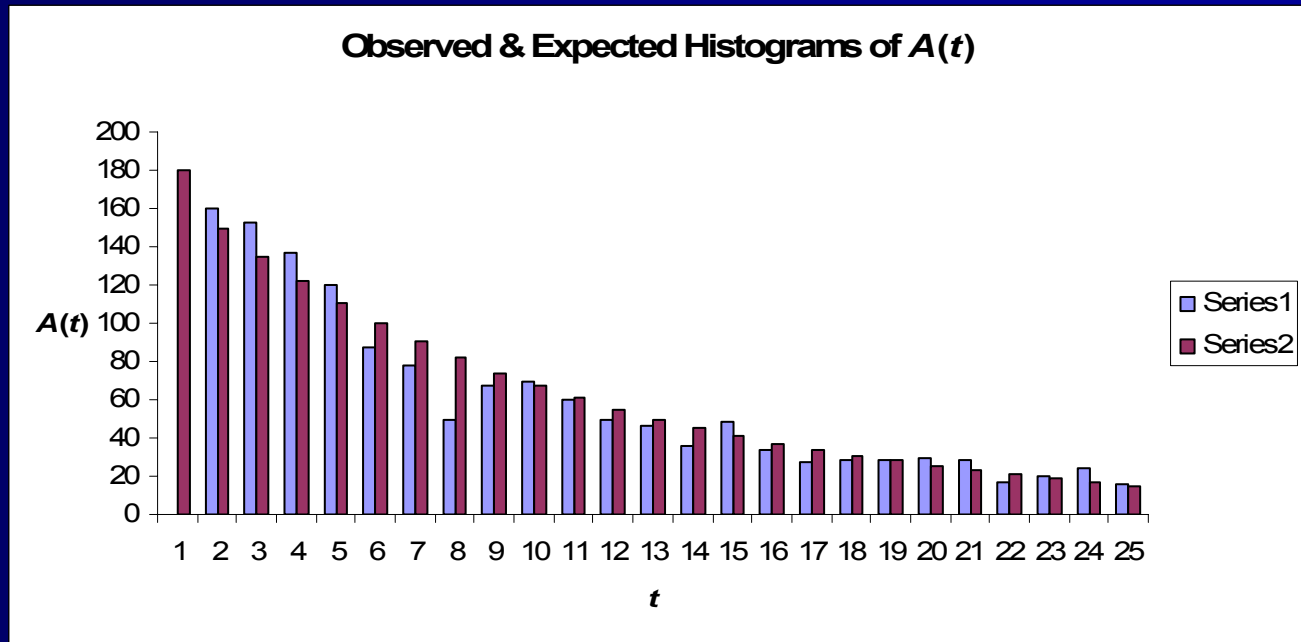
- $\rightarrow \tau_\mu = 2.1 \pm 0.092 \mu\text{s}$

- $\rightarrow \ln A_0 = 5$

$$A_0 = 170 \pm 7.9$$

# Observed & Expected Distribution

- $A(t) = 170e^{-t/2.1\mu s}$  (Series 2)



# chi-squared $\chi^2$ test

- Is data fit by  $A(t) = 170e^{-t/2.1\mu s}$ ?
- Test agreement between observed and expected distribution by computing the reduced chi squared:

$$\tilde{\chi}^2 = 0.46$$

- $\tilde{\chi}^2 \leq 1$ , so the observed and expected distributions are compatible

# Statistical Analysis

- $\tau_\mu = 2.1 \pm 0.092 \mu\text{s}$
- Is result statistically consistent with accepted value of  $\tau_\mu 2.1970 \pm 0.00004 \mu\text{s}$ ?
- Yes; discrepancy is  $0.10 \mu\text{s}$ , which is 1.1 times the uncertainty in  $\tau_\mu$

# Systematic Errors?

- cosmic ray background radiation,
- instrumental noise,
- muon does not produce a decay electron for detection in the scintillator
  - discarded events in which double pulses arrived more than  $5.3 \mu\text{s}$  apart

# Final Thoughts

- "Rossi coincidence circuit" represented the introduction of electronics to cosmic ray research (1939)
- For about 20 years, cosmic rays provided only way of discovering new subatomic particles
- Today, main focus of research on cosmic rays is their nature and origin

# Acknowledgement

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Professor of Physics
- Field of Specialization: Experimental  
High Energy Physics
- Research Interests: Electroweak force;  
Gravity waves