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Physics 410 - 510
Experiment N - 17

Lifetime of Cosmic Ray Muons
with
On-Line Data Acquisition on a Computer

Introduction

The experiment is designed to teach the techniques of particle detection using scintillation counters, delayed pulse timing measurements, on-line data acquisition of those measurements using personal computers and the statistical analysis of the acquired data to measure the muon lifetime to an accuracy of 1-2%. The decay rate of cosmic ray muons (μ-mesons) is studied by detecting those muons that stop in a scintillation counter and measuring the time between the signal from the stopping muon and the signal from the decay electron emitted in the muon decay. Because of lepton number conservation there are two other particles emitted in the decay. What are they?

The muons are produced in the decay of pions produced by primary cosmic rays (protons and heavier nuclei) high in the atmosphere. From accelerator experiments, we know that the charged pion lifetime is about 0.026 microseconds thus the pions decay high in the atmosphere and the fact that we see the resulting muons at sea level is dramatic proof of time dilation for relativistic particles. Assuming the muons are created 30 km above sea-level and travel at the speed of light, what is the minimum time they must survive to be seen in our experiment?

Description of the Experiment

Most cosmic ray muons have enough energy to pass through the scintillator without stopping, but those with a kinetic energy of less than 100 MeV lose enough energy to stop in the scintillator. The stopping of a muon and its subsequent decay into an electron (and neutrinos) is signalled by a double pulse from a photomultiplier tube viewing the scintillator. The time interval between the stopping pulse and the decay pulse is measured by an electronic timer to the nearest 0.10 μsec if the decay pulse occurs within 25 μsec of the stopping pulse. This time interval measurement is then transfered to the on-line computer by the serial interface. The electronics system is disabled until the processing of the event is complete, i. e., the computer resets the electronics via the serial interface after the data is accepted, and the system is ready for the next stopping muon. If there is no decay pulse within 25 μsec after the stopping pulse, the electronic timer is reset and the system is ready for the next stopping pulse. A block diagram of the apparatus is given in Figure 1.

The data are stored as numbers of counts in 256 time bins each of width 0.1 μsec. These data can then be displayed as a histogram of the raw decay distribution which must be analyzed to give the muon lifetime. The histogram consists of two components, the exponential decay and a uniform background of random coincidences due to the finite probability for two muon pulses to occcur within any time interval. The first step in the analysis is to extract the exponential part of the distribution and fit it to determine the experimental lifetime.

Because negative muons can be captured by the carbon nuclei in the scintillator (mostly carbon and hydrogen), they will have an apparently shorter lifetime. Since the positive muons are positively charged, they are not captured by the carbon nuclei and hence require no correction. Using the measured capture rate given in the article by Morewitz and Shamos and the positive to negative muon population ratio, the experimental lifetime can be corrected to give the lifetime for decay in vacuum.

Description of the Electronics

A block diagram of the apparatus is shown in Figure 1. Abbreviated data sheets of some of the components are given in Appendix A. Refer to the figure as you read the description given below.

Negative pulses from the photomultiplier tube are fed into the negative input connector. Since the light output from the scintillator is a fixed function of the energy deposited by the incident particle, the current pulse from the photomultiplier can be varied only by changing the high voltage and hence the gain of the photomultiplier. The tube used is a 10 stage tube and as a general rule the gain changes by roughly a factor of two per 100 volt increase in the high voltage. Because the cosmic ray rate is low and the fluctuations in energy loss in the scintillator are high, it is difficult to observe this behavior directly with an oscilliscope. The pulses from the photomultiplier are discriminated by using a comparator. If the pulse amplitude exceeds a preset amount, the comparator gives a standard width and amplitude output pulse (TTL compatible). This eliminates the ever present noise pulses from the photomultiplier if the high voltage is properly set. By connecting the oscilliscope to Test Point A, this standard pulse can be observed. The BUSY flip-flop is set by this pulse so that no new pulses can restart the timer until either the 25 μsec sensitive time is exceeded which then resets BUSY or the computer reset signal resets BUSY. The coincidence pulse, of course gets through to stop the timer and thus measure the delay between the two pulses.

The time interval between the stopping pulse from the discriminator and the subsequent pulse due to the decay electron is measured by starting a counter that is counting a 10.000 MHz clock with the initial stopping pulse and stopping the counter with the decay electon pulse (coincidence circuit output) if that pulse occurs within the 25 μsec sensitive time. To avoid having the initial stopping pulse fake a decay electron pulse, the 25 μsec sensitive time pulse is generated after a 0.5 μsec delay. The output of the coincidence circuit also provides a trigger signal to the serial interface to the computer. The interface upon receipt of this trigger signal issues a start bit followed by the 8 bit output word from the time counter. Scaler 2 counts the total number of these coincidence pulses during the run and should match the number of events received by the computer. By using the observed rate for long delay times, e. g. > 10 μsec., it is possible to check the frequency of the 10 MHz clock since the counting rate is known from the number of stop pulses measured by Scaler 1 and the total run time. A timing diagram for a stopping muon and its subsequent decay is shown in Figure 2.

Experimental Procedure

1. The first step is to find a suitable operating point for the high voltage for the photomultiplier. Turn on the apparatus and wait a few minutes for the electronics to stabilize. If the high voltage is too low it will mean poor efficiency for detecting the stopping muons and their decay products while a high operating voltage will lead to excess noise and a large accidental coincidence rate. Because the apparatus must operate for at least a day to obtain a sufficient number of events, it is important to choose a stable operating point so that small changes in the high voltage do not cause large changes in the counting rate. To find that "voltage plateau", measure the counting rate using Scaler 1 as a function of high voltage. A step size of 25 volts should be sufficient and run for long enough so that the statistical accuracy for the rate is better than 10%. Figure 3 illustrates the typical response of this apparatus. Select an operating voltage near the center of the plateau (flat portion) of the curve.

With the correct high voltage setting, use the oscilliscope to observe the various pulses generated by the electronics with the mode switch in the test position. Record the pulse lengths and their time sequences. Use the oscilloscope to roughly measure the frequency of the 10 MHz clock to see that it is working properly (Test Point B). The frequency of the clock is set by a quartz crystal which has an intrinsic accuracy of a few parts per million. If things look normal at this point you are ready to take data.

2. Become familiar with the operation of the IBM computer and its operating system. The data acquisition programs are located on the hard disk, \C:, in the directory labelled \MUON\. <u>These programs must not be altered</u>. You should create your own directory and copy the programs you wish to change and change only these copies. The program READDAT is used to transfer data from the input port to the memory and is written into the file DATAOUT.DAT. You may write your own program to display the data as a histogram. The program ANALYZE is an example of a program used to calculate the muon lifetime. You should write your own version to do the proper background subtraction and correction. (ANALYZE does NOT do the μ^- capture correction correctly!)

3. Take data for a few hours to get good estimates of the counting rates for muons (scaler 1) and for double pulses (scaler 2) so that you can estimate the overflow digit in long runs. From the observed rates, estimate the length of data run needed to collect sufficient data for an accurate (<2%) measurement of the lifetime. In your estimate, include the data needed to "calibrate" the 10

MHz clock rate using the random coincidences of the "background" rate at large times.

4. Take a data run long enough to satisfy the requirements for an accurate measurement of the lifetime. In your report, discuss the statistical and systematic errors in your data and in the final result.

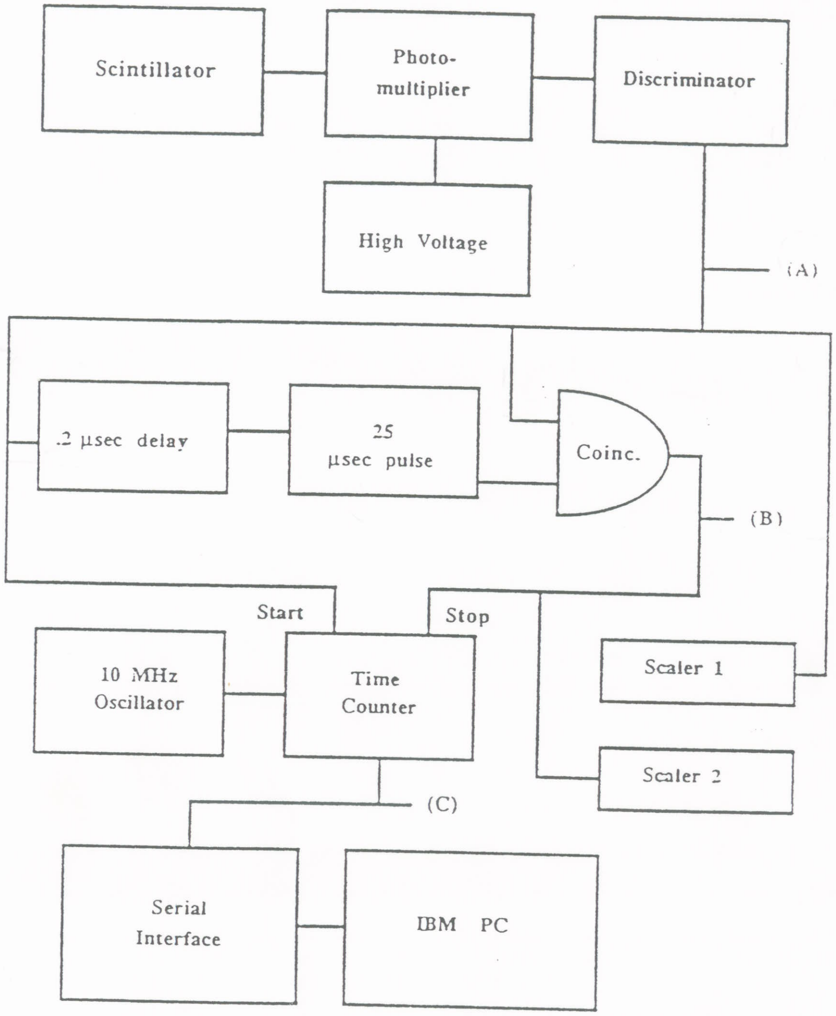

Figure 1. Block Diagram of µ-lifetime electronics.

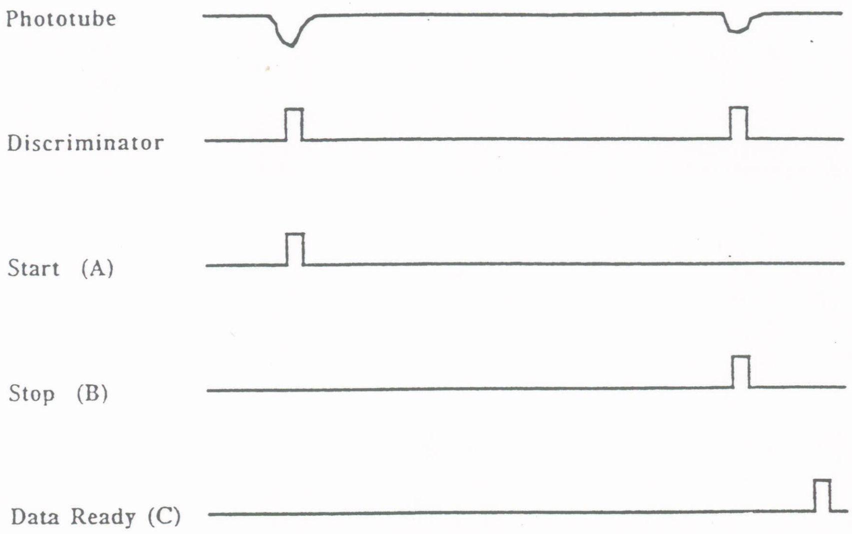

Figure 2. Timing Diagram for a typical stopping muon.

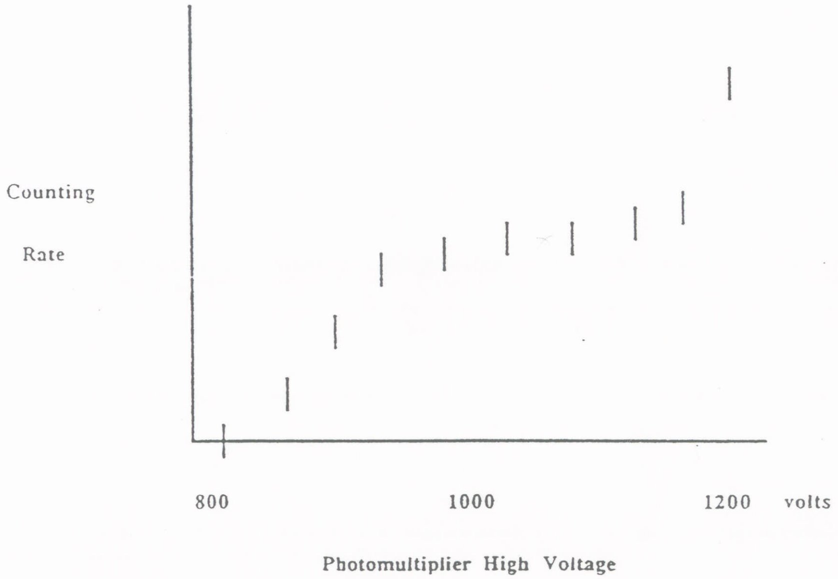

Figure 3. Typical counting rate versus high voltage for this setup

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```
      program readdat

      integer*2 comf,days,ecsec,eday,ehour,emin,emonth,esec,eyear
      integer*2 freq(256),hours,i,iarray(256),idati
      integer*2 key,minutes,ncr,scankb
      integer*4 elapsec
      logical*2 x,y,setdat,settim
      real*4 txt

      do 50 i=1,256
       freq(i) = 0
 50   continue

      write(*,1000) 'Enter number of days to run: '
      read(*,2000) days
      write(*,1010) 'Enter number of hours to run: '
      read(*,2000) hours
      write(*,1010) 'Enter number of minutes to run: '
      read(*,2000) minutes

      ncr = -1
      comf = idati(ncr,txt)

      write(*,*)
      write(*,*) 'Press return while holding down counter reset'
      write(*,*) 'DO NOT release counter reset'
      read(*,*)

      x = settim(0,0,0,0)
      y = setdat(1988,1,1)

      write(*,*)
      write(*,*) 'Press Ctrl-E to stop'
      write(*,*) 'Press Ctrl-T to view data'

      ncr = 1
      comf = idati(ncr,iarray)

      write(*,*)
      write(*,*) 'You may release counter reset'

100   ncr = 1
      comf = idati(ncr,iarray)

      do 200 i=1,ncr
       freq(iarray(i)+1) = freq(iarray(i)+1) + 1
200   continue

      key = scankb()
      call getdat(eyear,emonth,eday)
      call gettim(ehour,emin,esec,ecsec)

      if (key.eq.20) then
       write(*,1020) freq
       write(*,1030) eday-1,ehour,emin,esec
       write(*,*) 'Press Ctrl-E to stop, Ctrl-T to view data'
      endif
```

```
      if ((key.ne.5).and..not.(((eday-1).gt.days).and.(emin.gt.minutes)
     1 .and.(ehour.gt.hours))) goto 100

      elapsec = 86400*(eday-1) + 3600*ehour + 60*emin + esec

      open(7,file='dataout.dat',status='new')
      write(7,3000) freq
      write(7,3010) elapsec
      close(7)

1000  format('1',A\)
1010  format(1X,A\)
1020  format(1X,12I6)
1030  format(1X,'Elapsed time: ',I2,' days, ',I2,' hours, ',I2,
     1 ' minutes ',I2,' seconds')

2000  format(I8)

3000  format(12I6)
3010  format(I9)

      end
```