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Lifetime of Cosmic Ray Muons

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Introduction

The experiment is designed to teach the techniques to measure the muon lifetime to an accuracy of 1-2%. The decay rate of cosmic ray muons is studied by detecting those muons that stop in a liquid 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:

$$\mu^{\pm} \rightarrow e^{\pm} \nu_{\mu} \nu_{e}$$

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, the charged pion lifetime is about .026 microseconds so that the pions decay high in the atmosphere and the fact that we see muons at sea level is dramatic proof of time dilation for relativistic particles. For simplicity, we will ignore the decay rate difference between positive and negative muons and the effect of negative muon capture by the scintillator material nuclei.

Description of the Experiment

Most cosmic ray muons have enough energy to pass through the barrel of liquid scintillator without stopping, but those having a kinetic energy of less than approximately 100 MeV stop. The stopping of a muon and its subsequent decay into an electron (and neutrinos) is signaled by a double pulse from a photomultiplier tube viewing the scintillator. Light produced by the muon (the first pulse) and by the electron (the second pulse) bounce around inside the barrel to reach the phototube. The pulses are amplified and processed by a discriminator. The TDC is started by the first pulse and stopped by the second. The time interval between the stopping pulse and the decay pulse is measured by the TDC if the decay pulse occurs within 10 microsec of the stopping pulse. A gate defines this time interval, and another gate assures that the TDC would not receive another start signal within that 10 microseconds. This time interval measurement is then transferred to the on-line computer by the serial interface. A block diagram of the apparatus is given in Fig. 1.

The program running in the computer then bins the events into bins of 0.1 microsec width and these data are displayed as a scattered plot. The plot is the raw decay distribution which must be analyzed to give the muon lifetime. The plot consists of two components, the exponential decay and a uniform background due to random coincidences of to the second muon going through the scintillator. One can argue from the cosmic ray rate that this background can be ignored. The next step in the analysis is then to plot the data on an analysis program (like Excel) to determine the decay lifetime of muons. The data can be copied to a floppy disk file called MUON.CSV by hitting P on the keyboard.

Data Analysis and Decay Lifetime

The decay rate Γ is the probability per time that a particular muon will decay. For N muons, $N\Gamma dt$ would be number of decays in a time interval of dt:

$$dN = -\Gamma N dt$$

which leads to

$$N(t) = N_o \exp(-\Gamma t)$$

or with life time $\lambda = 1/\Gamma$,

$$N(t) = N_o \exp(-t/\lambda)$$

Here, N_o is the number of muons at t=0 and N(t) is the number of muons at time t. In this experiment we do not have coexisting muons that we observe to decay and count. Therefore, the meaning of N(t) and No are slightly different.

In this experiment No is not the number of muons present at t=0, instead it is the number of muons captured and decayed within the detector. N(t) is then the number of muons that have decayed in time interval t when a single muon entered the detector and decayed.

In Fig. 2 a sample data is plotted on a semi-log scale. From the above equation, we obtain that,

$$\log(N) = \log(N_o) - t \log(e) / \lambda$$

and therefore, the plot would have a slope equal to the coefficient of t at the above equation:

$$\text{slope} = -\log(e) / \lambda$$

which then yields the lifetime λ.

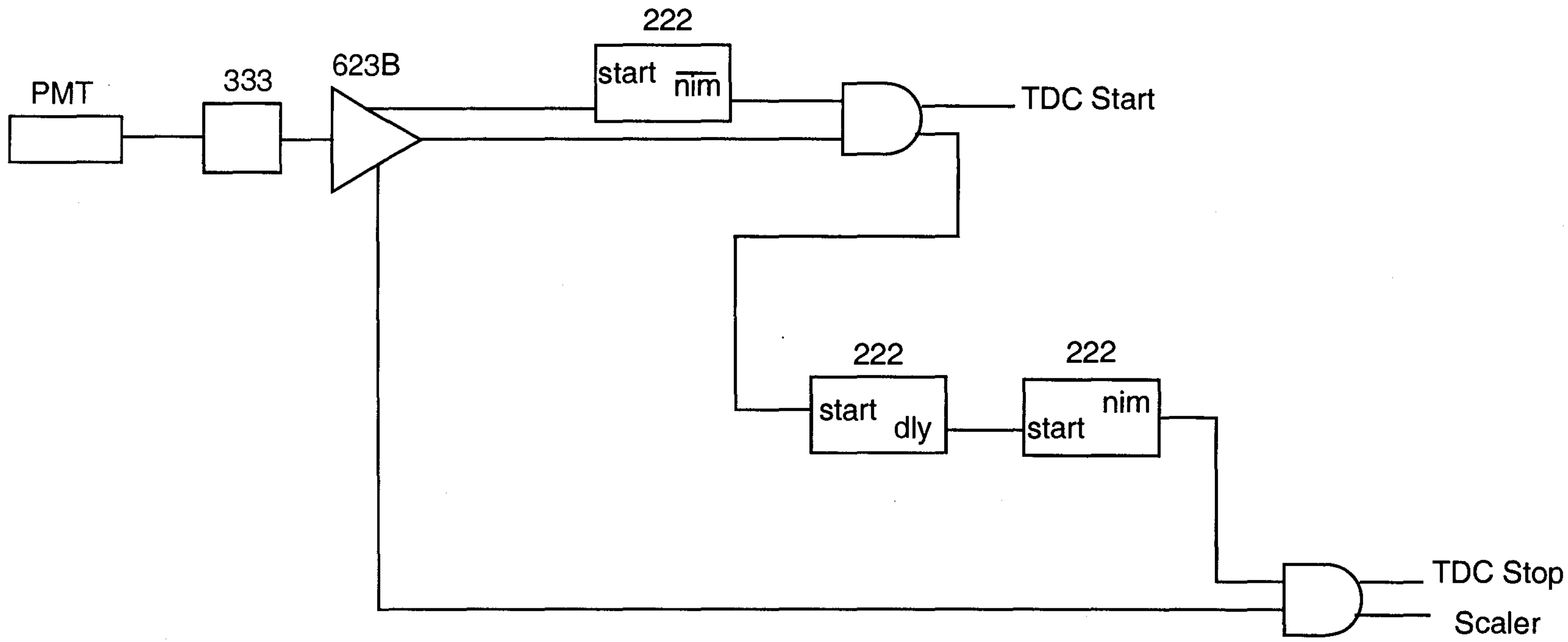

Fig. 1 The block diagram of the muon decay experiment electronics.

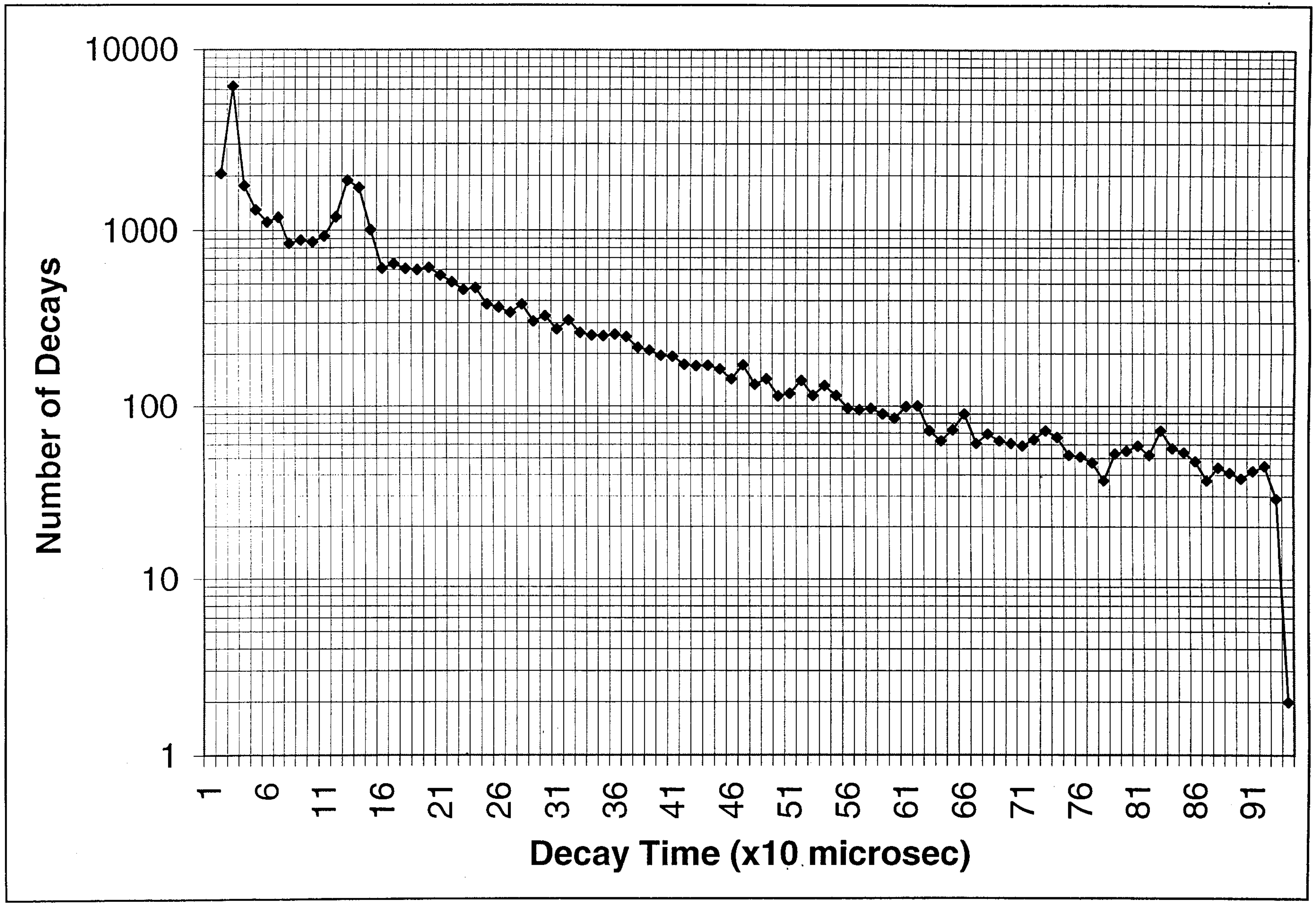

Fig. 2 Sample data plotted on a semi-log scale.