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MEASUREMENT OF THE MUON LIFETIME

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Abstract

The lifetime of cosmic ray muons is measured by stopping a sample of muons in a 10 gallon liquid scintillator detector and measuring the time difference between muon arrival and subsequent decay into an eleectron and two neutrinos. Events are collected over a 3-5 day period resulting in a sample of about 10,000 events.

1. Introduction

In this experiment you will measure the lifetime of cosmic ray muons that have stopped in a 10 gallon liquid scintillator detector. The apparatus consists of two 12in×12in plastic scintillation counters and a 10 gallon liquid scintillator counter each viewed by a single photomultiplier. The plastic scintillation counters are used to define an almost vertical trajectory for the liquid scintillation counter, and then all three detectors are placed in electronic coincidence. A small fraction of the defined vertical cosmic ray tracks will be muons which have stopped in the liquid scintillator. A stopping muon is then defined as a threefold coincidence between the detectors together with a subsequent delayed pulse from the liquid scintillator. The electronics for this experiment looks for delayed pulses out to 10 μsec after the threefold defining pulse. Since the muon lifetime is about 2 μsec, this means that decays over a five lifetime interval will be detected. This time distribuition of the delayed pulses is then fit to an exponential decay distribution to give the decay lifetime. The stopping muon rate in this apparatus is several events per min. so data will have to be collected for at least several days in order to measure the lifetime to approximately 1% precision.

Properties of the Muon

The muon is a heavy electron of about 207 electron masses or 105.66 MeV/c^2. Since the muon is heavier than the electron and is in the same family, the muon will decay into an electron. In order to satisfy conservation laws for leptons, the decay is into an electron and two neutrinos. The muons are made in the upper atmosphere as a result of primary cosmic rays interactions which have produced a shower of particles, some of which decay into muons. Due to attenuation in the atmosphere of the other shower components, only muons tend to be left at sea level. The cosmic ray rate at sea level is about 0.01 cm^{-2}sec^{-1}steradian^{-1}, with a μ^+/μ^- charge ratio of about 1.2.

The free muon decay lifetime is well measured and has been determined to be $2.19703 \pm 0.00004 \times 10^{-6}$ sec. However, only the positive muons will decay freely 100% of the time. Negative muons also have another disappearance channel in matter, which is muon capture by a proton resulting in a neutron plus neutrino. This has the possibility of happening to a negative muon, since a negative muon will be captured into a Bohr orbit about the nucleus like an electron, but with a Bohr radius about 200 times smaller than that of the electron. The resulting small radius orbit effectively means that the negative muon spends a large fraction of time inside the nucleus, and thus will have a sizeable probability to be captured by one of the protons inside the nucleus. Since the total decay for negative muons now consists of the sum of the free decay rate plus the capture rate, the lifetime of negative muons in matter will differ from that of positive muons. The capture rate for negative muons will obviously be Z dependent, and it turns out that the free decay rate and the capture rate are about equal for Z=10. Thus for Z=10 the negative muon lifetime would then be 1/2 the positive muon lifetime. It is also the case that the capture rate goes as Z^4, so the above information will allow you to calculate the capture rate for any effective Z, given the free muon decay rate. In this experiment you will be measuring the average lifetime of a mix of positive and negative cosmic ray muons stopping in mineral oil. Mineral oil is a CH_2 chain with an effective Z of about 5.

2. Apparatus

The apparatus consists of three detectors, fast electronics to define detector coincidences, a time to pulse amplitude converter (TAC) to measure the time difference between stopping pulses and a subsequent decay pulse, and a computer controlled pulse height analyzer (PHA) which contains an analog to digital converter (ADC) and data acquisition software.

<u>Scintillation Counters</u>

The two defining scintillation counters, T1 and T2, are each 12in.×12in. ×.63in. and are viewed by Amperex 2200 10 stage 2 in. photomultiplier tubes. The voltage divider chains are set for <u>negative</u> high voltage operation. The current operating voltages are HV(T1)= −1770 V and T2)= −1770 V. These voltages will operate the tubes at approximately equal gain.

T3 is a 10 gallon container filled with ND 307 liquid scintillator and viewed by a single EMI 9870 12 stage 5 in. semi-spherical photomultiplier. The voltage divider is set for <u>positive</u> voltage with a current operating voltage of HV(T3)= +900 V. This operating voltage has been chosen as a best compromise for optimum signal to noise. The T3 detector itself is a fiberglass tank painted internally with a special reflecting coating. The photomultiplier is mounted so that the photocathode is immersed into the liquid and the anode protrudes through a hole in the cover of the container. The output of the photomultiplier is taken from the last dynode of the multiplier chain rather than the anode so the output pulse is positive rather than negative. The reason for doing this is that the photomultiplier anode output is connected to an internal amplifier which requires additional power, and we have found that the amplification is not necessary for good operation.

The liquid scintillator is essentially mineral oil with additives to make the scintillations.

The Electronics

The major components of the electronics are high voltage supplies for each photomultiplier, a pulse shaping discriminator for each counter output, a logic unit to make the three-fold coincidence between the counters, a time to pulse height converter to produce an analog pulse proportional to the start-stop time difference, and an analog to digital converter/computer combination to serve as the data acquisition system. There is also a scaler for measuring counting rates.

All electronic modules except the PHA/computer are contained in a NIM bin which provides module power. The discriminators are LeCroy Corp. model 621 Quad Discriminator units, and the logic unit is a LeCroy Corp. model 365 4-fold logic unit. The key component is an Ortec model 566 time to pulse height converter with a wide range of time scales. The scales are normally set to 10 μsec full scale for the time and 10V full scale for the output voltage. This means that a 10 μsec start-stop time difference will produce a 10V output pulse with a linear response for intermediate values. The power supplies and the counter unit are Ortec models. There are also pulse generators available for calibrating the model 566.

3. Procedure

The basic procedure consists of several well defined parts.

1. First form T1-T2 coincidences and measure the rate.
2. Put T3 in coincidence to form T1-T2-T3 coincidences and measure the threefold coincidence rate. Also measure the T3 rate.

3. Use T1-T2-T3 coincidences as the start pulses and a T3 discriminator output as the stop pulse for the TAC unit. The start pulse should be delayed by a small amount so that stop pulses corresponding to zero time difference arrive before start pulses at the input to the TAC unit. This will prevent a large accumulation of pulses at low pulse height which have nothing to do with muon decay and which block real decay events.

4. From the measured start and stop rates, calculate the expected rate for random start-stop pairs. Random start-stop pairs will be the major background underneath the muon decay time distribution. It should turn out that this rate is small compared to the muon decay rate.

5. Calibrate the TAC/ADC combination and check the linearity. This is done by sending the TAC unit start-stop pulses from pulsers. The start-stop time can be varied over the full range and the whole system can be calibrated in this way. The oscilloscope is used as a time reference. When this is done you will have a number for the time per pulse height analyzer bin. This should agree well with what is expected, viz. that 10 μsec should correspond to 10V. However the PHA full scale voltage for 256 channels is only 8.0 V which corresponds to 8.0 μs.

6. Estimate how long you have to run to achieve a desired precision in the lifetime measurement. You have to run for a short while to measure the muon decay rate. It should be about 2.5/min. You can then decide how long you have to run to accumulate the number of events to establish a desired precision in the lifetime. You should find that you will want to run at least 24 hours.

7. When all the above points are satisfied you can start a run using the UCS20 software that controls the PHA.

4. Analysis

At the end of the run you will have 512 channels of data in the PHA active memory. The suggested procedure is to transfer the data to the SigmaPlot analysis package where the data can be edited and fit to the appropriate functional form. The channels at both the lower and upper end of the distribution should be examined to see if there are 'end' effects which may require removing some channels from the fitting procedure. It is also convenient to rebin the data into a smaller number of channels, e.g. 10 or 20 points per bin. The editing of the data can all be done from within SigmaPlot. Finally, the data must be fitted to determine the lifetime. SigmaPlot has the capability to perform a weighted fit, using the appropriate Poisson distribution statistical weights.

1. At the end of the run, save the data as a text file (tab separated variable file (**.tsv**) so that you can read the data into SigmsPlot. Print a copy of the spectrum from the UCS20 program.

2. You will at some point want to transfer the data text file to SigmaPlot for analysis and making spectrum figures using a floppy disk to transfer to one of the laboratory work stations. Convert the data to a smaller number of channels (10 or 20 points per bin) by regrouping the data. This can be done within SigmaPlot by using the TOTAL, CELL and COL functions. For example, if you want to add the first ten rows of column 2 data and put it in CELL(5,1) (column 5, row 1), execute the transform: CELL(5,1) = TOTAL(COL(2,1,10)).

3. Make a non-linear weighted fit to determine the decay constant and hence the muon lifetime. The fit should include a term for the random background. The fit result for the background term should be compared to the random background calculated from the singles rates and PHA time range.

4. Compare your lifetime result to that expected for the free decay of muons. Remember that this is not what you are measuring directly. You are measuring the decay parameter for a mix of muons that decay freely (all the μ^+ and some of the μ^-) and undergo nuclear capture (the rest of the μ^-). Since the μ^- have two disappearance channels while the μ^+ only have one, the μ^+ and the μ^- have different lifetimes. Since the two lifetimes are close in value, you will fit the data as if there is a single lifetime, but you will have to make a correction for this effect.

5. Questions

Include in your notebook the derivation for the following questions:

1. Derive a formula that relates τ_{meas} in terms of τ_0, r, and Z, where τ_0 is the free decay lifetime, r is the μ^+/μ^- ratio, and Z is the average Z of the liquid scintillator mineral oil.
2. How many events (N) are required for a given precision in the lifetime $(\delta\tau/\tau)$?
3. What limits the precision of the determination of τ_0?
4. Calculate the maximum energy of the decay electrons (express in MeV).